The Swedish Foodprint

An Agroecological Study of Food Consumption

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Abstract

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Food production capacity in the world may be approaching limits, while population continues to increase. Improving living standards also tend to change consumption patterns to be more demanding on resources. There is a link between resources used and amount of arable land needed for food production. The more, mostly non-renewable, resources we use, the less agricultural land is needed. However, this study stresses that food production is dependent also on other land, in addition to agricultural land, for environmental support.

The term *foodprint* was introduced as an attempt to visualize our dependency on resources, mainly land area and ecosystem services, for our food consumption. The *foodshed* approach has been used together with *footprinting* methodology and a systems ecology approach. In this thesis the food system is considered in a holistic way, respecting all contributions, by man as well as nature, supporting food consumption.

The *foodprint* is made up of *direct* and *semi-direct* agricultural area and appropriated *indirect* support area. Direct land area used for food consumption in Sweden for 1997-2000 was on average approximately 3.7 million ha or 0.41 ha per capita. Semi-direct land (fallow land) use for the same period was 260 000 ha. A *modified consumption pattern* would decrease the agricultural area required by 14%. The indirect land use for ecosystem support was estimated at 3.7 to 10.8 million ha, or 0.41 to 1.2 ha per capita, depending on approach used, with around 19 000 ha of degraded land, equal to 0.002 ha per capita.

An *emergy* calculation further develops the *foodprint* approach and comprises all resource use, including historical. An *emergy footprint* provides evidence that the area needed to support Swedish food consumption in 1996 was extensive. The emergy support area was 40 times the agricultural area, or 3.6 times the land area of Sweden! This provides a hint that we would need much more area if we wanted to, or had to, produce the same agricultural products using only locally renewable resources.

Key words: consumption patterns, ecological footprint, ecosystem services, emergy, foodshed, sustainable food system, systems ecology

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Foreword

Few things are certain in the world, but then again – some are! We have always eaten for our survival, and most likely we will still have to eat to survive in future. But *what* we eat and *how* we get it has changed drastically over history. Most of us eat every day. It is a necessity of life. However, we have little knowledge of how our consumption affects our natural resources, the footprint of our food consumption, *i.e.* our *foodprint*. What we eat is a major determinant of how natural resources are used and misused. When we eat an apple it may make no difference to us where it comes from, as long as it tastes like an apple and looks like an apple. But if it comes from New Zealand or from France, or from our own back yard, it will have had very different impacts on our environment and on other people's lives. So which apple should one choose?

One day I read that Swedes were eating more meat and bananas than before. Based on what I had learned, it immediately made me think that more agricultural land in other parts of the world was being used on our account. Bananas are not grown in Sweden, and a substantial amount of the animal feed used in Swedish meat production is imported. We also need more agricultural area overall, because more area is required to produce one kilogram of meat protein than one kilogram of crop-based protein. 'Is this the way we are heading?' I thought. 'Towards more area per person for food production, and moving it more and more over our borders to other parts of the world?'. If so, is this a problem for our future well-being, future generations, sustainability and fairness between poor and rich; the hungry world and the satisfied world, to use the words of Georg Borgström (1973)? Are our consumption patterns compatible with a growing global population and loss of non-renewable resources such as agricultural land, fossil fuels and freshwater, and our ecosystems ability to supply us with their services? If not, what should we eat?

I remember hearing as an undergraduate student about two digital counters placed next to each other; one with numbers increasing for every new person added on to the global population, and one with numbers decreasing for every hectare of agricultural land being lost due to soil degradation. This really concerned me. The population is increasing while land is being degraded and lost. Yields are increasing, but then consumption patterns are changing to be more resource- and area-demanding. To add to the stress, most resources used are non-renewable. This seemed to be an unsolvable equation to me. As I continued to read, it also seemed that way for the many scientists I came across (Malthus, 1798; Borgström, 1973; The World Commision on Environment and Development, 1987; Meadows, Meadows & Randers, 1992; Pimentel *et al.*, 1999; Pimentel & Pimentel, 1999; Novartis, 2001; Gilland, 2002). They all conclude that drastic changes have to be made. At a conference in Uppsala, Sweden on sustainable agriculture, Professor Ikerd from the University of Missouri, Colombia, USA (Ikerd, 2003) put it this way: 'We will not be able to feed the future world with today's agriculture. We have a 50-year window where we have to change either our population, or consumption patterns.'

My graduate studies started out as an agroecological study of integration between farming and households. The hypothesis of the study was that a close integration between production and consumption on a local scale was more resource efficient and sustainable than today's food system. When I started to study the larger system supporting my system of interest on the local scale, I got stuck out there in the big picture, trying to understand the resource base for our food consumption. It also occurred to me that maybe it was not only a question of *where* our food is coming from, but also a matter of *what* we eat and *how much* of each food.

With the choices you make in the grocery store, you have an impact on the lives and environments of other people. One could also say 'a better world starts in our kitchens'. My interest in analysing Sweden's food consumption is not so much a fear of us not having enough food, but of our consumption lessening the chance for people in other parts of the world, and future generations, to have enough food by degrading their environment. Are we importing food and exporting problems we wish to avoid ourselves?

I first wanted to give my thesis the title 'There is No such thing as a Free Lunch'. Food costs, and not only in monetary terms. I mean that resources and services that may seem free, such as natural resources and ecosystem services, must be paid for by someone some way or another. If the consumer doesn't pay for the work that has been put into the production – let it be the work of natural resources or that of man – then most probably someone else has had to pay. Or someone else will pay in future because present generations have lived on an excessive ecological credit.

Food consumption is a complex field of study supported by an intricate and non-transparent system, with many who are experts on parts of this system. It is equally important that some of us are generalists who focus on the whole. I would like to think of myself as a systems thinker having a systems approach to something really important – food for my son and his friends and their children, on this planet, in the future.

Acknowledgments

This thesis is mostly my own idea and work. No other woman or man can be faulted for errors herein. However, many are those to be acknowledged for supporting and helping me, both professionally and personally, along the way. Since it has taken some years to follow it though, many are those that I have met along the way.

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I'd like to thank all the friends I made in Gainesville during my studies at the University of Florida during 1998. You all made it a good year in many ways. I'd especially like to thank Dr Mark Brown for his teachings and assistance in finding accommodation and an old bike. I thank professor HT Odum and Dr Brown, and their colleagues and students, for the interesting seminars under their guidance. I thoroughly enjoyed being able to attend them. Special thoughts go to Rosemary Portella who from the first day introduced me to everybody and everyplace, including a trip to Key West, Ravik Nijbroek for taking me salsa dancing on lonely evenings, Mark Nelson for introducing me to Yoga which has made many things easier ever since, Steven Doherty and his family for inviting me to your home and John Juston for taking me camping in numerous Floridian State Parks in your old Toyota truck (and for marrying me).

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Many are the bananas that have been eaten during the making of this thesis. And many more are the cups of strongly brewed coffee. I shudder to think of the *foodprint* this thesis has contributed to. I hope that the emergy invested in me will contribute to a positive feed-back on other peoples lives and environments, in one way or another.

Contents

Abbreviations

DA	Direct agricultural area
EF	Ecological Footprint (according to Wackernagel and Rees (1996))
EFF	Emergy footprint factor
ELR	Environmental loading ratio
EYR	Emergy yield ratio
FAO	Food and Agriculture Organization of the United Nations
FLO	Fair trade Labelling Organization
IFPRI	International Food Policy Research Institute
IWMI	International Water Management Institute
MA	Millennium Ecosystem Assessment
SCB	Statistiska Centralbyrån (Swedish Statistics)
SIWI	Stockholm International Water Institute
Sej	Solar emjoule
TNC	Trans-national Corporations
UN	United Nations
UNDP	United Nations Development Programme
USDA	United States Department of Agriculture
WRI	World Resource Institute
WTO	World Trade Organization
WWI	World Watch Institute

Introduction

The objectives

The objectives of this thesis were to:

- Investigate the impact of contemporary Swedish food consumption on local and global resources, mainly agricultural land area.

- Explore how foodshed analysis, ecological footprinting and emergy analysis can visualize our appropriation of resources for food consumption in contemporary Sweden.

The studies

I begin the thesis with a background to current food consumption; the food system and the resources needed, consumption patterns that affect it and trends that may change it. I also describe and discuss the different methods and approaches used in my work. I then move on to study the Swedish food system.

The first study, *Agricultural area for food consumption in Sweden 1997-2000 – The direct and semi-direct areas*, was the most extensive study, including a large database of the food consumed in Sweden in the time period 1997-2000. Here I calculated the total agricultural area appropriated for our food consumption during this period, both food produced domestically and imported. The agricultural area is made up of *directly* and *semi-directly* (fallow land) appropriated land area. The areas were divided into different food categories, investigating how much area each category appropriated. In this study I also discuss how a modified consumption pattern, designed to be more sustainable and healthy, could change our direct use of agricultural area. The diet has been developed for Sweden by nutritionists in collaboration with a reference group of scientists with agendas in food, environmental and agricultural issues.

In the following two studies I explored the *indirect areas*, the support areas needed for our food consumption, in addition to the directly and semi-directly agricultural land appropriated. The support area is the environmental area supporting human activities, in this case food consumption. The second study, *The Swedish foodprint – Directly and indirectly appropriated area for food consumption in Sweden 1997-2000*, introduces the *foodprint*, where the *indirect area* for land degradation and ecosystem services is estimated and added to the direct and semi-direct area in the previous study.

The third study, *Emergy synthesis and emergy footprint of the Swedish food system 1996*, is an emergy evaluation of the food system supporting food consumption in Sweden 1996. The results of this study were first presented in the paper *Swedish food system analysis 1996* by Johansson, Doherty & Rydberg (2000) at the conference: *Emergy Synthesis: Theory and Applications of the*

Emergy Methodology. First Biennial Emergy Analysis Research Conference, in Gainesville, Florida, in September, 1999. However, in this chapter of the thesis I have also calculated an *emergy footprint* of the Swedish foodsystem, further developing the *foodprint* concept. The paper can be found in appendix B.

Please note that throughout my work I use the terms *North* and *South* instead of *developed* and *developing* countries. These terms are frequently used by researchers and analysts working with rural development and related studies, and I feel that they are appropriate to use here. By *agricultural production* I mean what in the literature is sometimes referred to as primary production, which happens on the farm, to be distinguished from *food production,* which happens in the entire food system, *i.e.* from agricultural production through processing and distribution to consumption of food. I also use the term *arable land* for what is sometimes referred to as *crop land*, and *pasture land* instead of *grazing land*.

Background

Food is life! In the Swedish language food translates to *livsmedel* (*liv* = life, *medel* = means, resources) *i.e.* 'the means we need to sustain life'. We need food and its contents of nutrients, proteins, fats and carbohydrates in order to live. However, food can also mean much more than just sustenance. Eating good food together with family and friends increases our quality of life. Many of our holidays, traditions and childhood memories are closely linked with certain foods.

Almost all our production of food requires agricultural land. The area of land needed to feed a population depends on yields per ha, which in turn depends on factors such as production systems, farming practices, amount of external inputs, soil quality, climate. The land area also depends on the consumption pattern of the population – how much of certain foods are consumed – since different foods have different area requirements. For example, land requirements are around ten times larger for meat than for processed protein food based on soya beans (Reijnders & Soret, 2003). Finally, the area of agricultural land needed depends on the level of losses and spoilage in harvest and storage. The more of the harvest that makes it to the kitchen table, the smaller the agricultural area needed.

We are dependent on ecosystems, both natural and managed, supplying us with goods and services. Food, clean air and water, useful energy and recreational experiences are just a few of these services that our ecosystems provide. The ability of ecosystems to supply us with services and goods is frequently taken for granted, often because many of them are free of charge and because we do not see them. Our lack of recognising the work of nature has therefore led us to overuse and degrade many of these ecosystems, thus decreasing their ability to do work. The well-being of both present and future human populations is being jeopardised by the rapid changes in ecological life-support systems. Many experts are concerned with the ability of the planet to feed a growing population, with fewer available resources and degrading ecosystems.

A global perspective

> 'Before you've finished your breakfast this morning, you'll have relied on half the world.'
>
> Martin Luther King Jr.

Abundance and starvation at the same time

With current production systems, the agricultural land available produces enough food world-wide to feed more than 6 billion people, the size of the current global population. Nevertheless, people are still dying, or live greatly impaired lives, due to lack of food, a painful sign that we have not yet been able to create equity. About 850 million people in developing countries still do not have access to enough food to meet their daily needs (FAO, 2004). The reasons for this are many. Millions of people face starvation owing to conflicts in their own or neighbouring countries, inadequate regimes and infrastructural problems.

Inappropriate and unsustainable production systems, environmental degradation and lack of local resources prevent enough food being produced, even though it could. At the same time farmers in the North are economically stimulated to set aside land because they produce too much. The food system, as part of the current larger economic system promoting global trade, was originally not a system developed to feed the entire world. Stronger players on the market can use their advantages to stay ahead of the game, creating un-fair trade. We therefore have abundance and starvation at the same time.

Today, consumers in the North are provided with an abundance of always-available foods, and few consumers have much knowledge of the biological, social or technical parameters and implications of food production in the global context. How can they, when the food system is so large – both in size and in distribution over the globe? What we eat comes from a 'global everywhere', yet from nowhere that we know in particular, to use the words of Kloppenburg & Lezberg (1996). For anyone walking around the average Swedish supermarket, it is hard to understand that there can be any limits to our consumption. It is all there, from everywhere, every time you step in. "So what is the problem?" the consumer may think. No underlying problems are visible at the supermarket. One cannot see the potential health problems of the workers in Nicaragua when buying bananas in Sweden, or the effects on the rainforests in Brazil when buying Swedish meat. In the latter case it is even hard to see the connection, because the food system is so non-transparent. Not only is Brazil on the other side of the globe so one cannot see the rainforest converted into soya bean-producing fields or the effects that this has on the ecosystems, but few consumers may even be aware that pigs and other farm animals eat imported soya bean products. As much as 80% of the ingredients in manufactured feeds used in Swedish meat production are imported on a calculated area basis (Deutsch, 2004), so it may even be questioned *how* Swedish the meat actually is. To the Swedish consumer, it is not obvious that so many resources come from abroad and it is not easy to see the connections between food consumption in Sweden and the environmental and social impacts of the agricultural productions systems happening somewhere else. This is even more difficult if consumers do not recognise that much production happens outside national borders. One in ten children in Sweden thinks that bananas are grown in Sweden. One in four children in the U.K. and the Netherlands believes that oranges and olives grow in their own countries, and one fifth of children in Finland and Sweden believes that peaches grow in their own countries (Holst, 1999).

The food system

The term *food system* is frequently used in discussions about agriculture and natural ecosystems, food science, nutrition and medicine, to describe the complex set of activities and series of transformations involved in providing food for sustenance and nutrients for maintaining health. The food system includes all processes involved in keeping us fed: growing, harvesting, processing, packaging, transporting, marketing, consuming and disposing of food waste (Dahlberg, 1993; Tansey & Worsley, 1995; Johansson, Doherty & Rydberg, 2000).

The development of the modern food system picked up speed during the European industrialisation. Factory workers and a growing urban population in the cities needed food, so farmers in rural areas no longer merely produced for themselves, but started to produce agricultural products for an industry that processed the raw materials into food. New technology for processing and transportation of food allowed mass production and marketing. Thus, the industrialised food system was born.

Sometimes the system is described simply as a chain of processes between land and mouth, from farming to processing, through marketing and distribution and on to the consumer at the end of the chain (Singh, 1986). However, some researchers like to define the food system in broader terms, as the simple definition cannot capture the complexity of the food system. The term *food system*, instead of *food chain*, implies that it is a system with interconnections and feed-back. It is a complex system with many interdependent parts (Tansey & Worsley, 1995).

The food system is part of many systems, both large and small, for example the biosphere, our local ecosystems, our economic and social systems, agricultural systems, food distribution systems, and even smaller systems such as farms, fields and organisms. When analysing and investigating the food system, these need to be recognised. Approaches and methodology to do so were used in this thesis and are discussed under *Methodological framework* later in this thesis.

Trade globalises the food system

The system that supplies us with food today is global. This means that what we eat not only affects *us*, but also has an impact on environments and people's lives and resources outside our own borders. One key factor influencing land use patterns on the global scale is international trade. No longer do countries provide merely for their own population, but act as players on the global marketplace. Global food trade has increased in recent decades. For example, between 1961 and 1999 there was a four-fold increase in the amount of food exported world-wide, from 190 million tonnes to 774 million tonnes. It is noteworthy that this increase is not proportional to the increase in production – it is just that a greater proportion of the food produced is circulating on international markets (Millstone & Lang, 2003).

A global food system has many benefits for the consumer. It enhances our lives with foods we would otherwise not have, like coffee, cocoa, tropical fruits and spices. People living in the Nordic countries are able to enjoy orange juice and coffee for breakfast. A global food system allows food to be grown in regions of the globe where climatic conditions are most suitable. Trade has the potential to become an important tool for redistributing resource flows and closing the ecosystem support gap around the globe, according to Deutsch *et al.* (2000). It can be seen as distributing sunshine to colder areas, which in turn can lead to fewer resources being used for artificial temperature and light in greenhouse production of vegetables and fruits. Some claim that food trade is one way of distributing freshwater resources, by producing food such as grain in rainfed areas and exporting it to dryer areas where freshwater resources are scarce, *i.e.* trade of *virtual water* (Falkenmark *et al.*, 1998). If the exporter is more productive per unit water than the importer, such trade reduces global water use and leads to a global water saving (SIWI & IWMI, 2004). Trade may also bring us mentally closer to other cultures by adopting some of their cuisine, which could benefit global peace and understanding.

Some claim that a global food system provides much-needed economic benefits to countries under development, as long as it is fair and on equal terms for the South and the North (Farnworth, 2004). However, not everybody benefits from trade as it is today. According to the latest FAO report on the state of food insecurity in the world, the globalisation of food industries and the expansion of supermarkets present both an opportunity for countries in the South to reach lucrative new markets, and a substantial risk of increased marginalisation and even deeper poverty (FAO, 2004). The food system is largely developed, run and promoted world-wide by economic institutions in the rich and powerful industrial nations, making it harder for smaller businesses to compete (Wimberley, 1991; Bonanno *et al.*, 1994; Tansey & Worsley, 1995; Lezberg & Kloppenburg, 1996). Small producers are vulnerable on the global market. Centralised buying by supermarket chains can lead to smaller producers being squeezed out of the market as they are unable to produce the quantities required. International trade of *e.g.* fresh products is complicated. Not only do Europe and the Northern American countries apply protectionist quota and tariff systems, but they also have high quality requirements for the produce. Consumers are no longer willing to accept seasonal availability of *e.g.* fruits and vegetables. Fresh fruits are usually shipped on a weekly basis and require sophisticated logistics to ensure that they look fresh and appetising once they arrive in the shops. All this involves high costs for the producer organisations, making it very difficult for small-scale commercial farmers to successfully compete with the big companies dominating the export business (FLO, 2004). Thus the power is concentrated to a few, often transnational, corporations (TNCs), *e.g.* Nestlé, Monsanto, Unilever, Tesco, Wal-mart, Bayer and Cargill (ActionAid International, 2005). All are said to have expanded in size, power and influence in the past decade. The 30 largest supermarket chains now account for about one third of food sales world-wide (FAO, 2004).

Agribusiness tends to gravitate to areas where government intervention is minimal and wages are low, or in which costs can be reduced through mechanisation and increases in scale, or both (Bonanno *et al.*, 1994). The increasing agribusiness with palm oil in South East Asia and soya beans in Brazil are examples of where minimising economic costs for business can have large environmental and social costs for the country of export (Hardter, Chow & Hock, 1997; Fearnside, 2001). Tropical and subtropical areas have an appeal for agribusiness because the climate permits production of many crops all year around, and these are typically countries in the South. Wimberley (1991) claims that the activities of TNCs promote hunger in the Third World. Per capita consumption of calories and protein was compared to TNC investment penetration. Countries with minimal TNC penetration were estimated to have gained approximately 700 more kilo calories (2900 kilo joules) and 20 more grams of protein consumption per person per day than countries with maximum transnational corporate penetration (Wimberley, 1991). This corresponds to a whole meal for an adult, or a whole recommended daily intake of food for a young child.

Many countries in the South have been encouraged to improve their foreign earnings by increasing their exports in order to pay off international debts, while high-income countries in the North kept their agricultural markets more protected. In the summer of 2004, however, the World Trade Organization (WTO) signed new agreements, which no longer allow countries in the North to protect their markets. These agreements are crucial to bolstering international economic growth and helping countries in the South to integrate into the global economy (WTO, 2004).

Fairtrade labelling has been constructed to facilitate the support of socially, environmentally and economically fair production systems through consumer choice. It aims to create direct and long-term trading links with producers in developing countries, and to ensure that they receive a guaranteed price for their products on favourable financial terms. By enabling consumers to recognise and buy Fairtrade products, disadvantaged producers are offered a special market segment to gain export experience and to develop their business, in order to compete with larger corporations (FLO, 2004).

A large food system can increase our food security on one hand, and decrease it on the other. When the food system is large we become more vulnerable, thus decreasing food security. Due to free trade and the ability to transport animals long distances, we are all more exposed to diseases like BSE, salmonella and foot and mouth disease, which has become evident during recent years in the EU. Food fraud and adulteration are also problems in a large and hard to overview food system (Tansey & Worsley, 1995). On the other hand, being able to import food enables us to keep a stable food supply over the years, since some years allow for higher crop production than others, thus increasing our food security.

What else than fairtrade labelling can be done to make up for the distress that the modern, global food system may bring to people and nature? To consume food sustainably, some assert that we need to bring trade down to a minimum and go local, becoming ‘own fed’ and ‘native to our place’ (Jackson, 1994). Research suggests that eating seasonally and locally can save on transportation, packaging and energy (Carlsson-Kanyama, 1998a; Thomsson, 1999). Several food system approaches that feed us with locally produced foods have been offered to us as environmentally sustainable alternatives or responses to the globalised and unjust food system, including *e.g. foodshed projects* to promote local food systems (Getz, 1991; Kloppenburg, Hendrickson & Stevenson, 1996) and *community supported agriculture* (CSA), where consumers support local farmers by paying for a share and in return receiving farm products of the season on a regular basis, directly from the farm. Researchers at Cornell University in the USA promote the concept *community food system* as ‘an ideal – a food system in which food production, processing, distribution and consumption are integrated to enhance the environmental, economic, social and nutritional health of a particular geographic location' (Wilkins & Smith, 1999). Farmers' markets are another example, in which local farmers sell their products at a local market place one or more days per week. In Sweden some farms sell their products, such as vegetables, bread, meats, directly on the farm, while in summer some farmers offer a pick-your-own facility for fruits, vegetables and berries.

Swedish food trade

Sweden is a player on the global food market and Swedish consumers enjoy many imported products that cannot be produced within the country. Swedes consume most bananas per caput in Europe, and per capita coffee consumption comes second in the world only to that of our neighbouring Finland (FAOSTAT, 2004).

The trade statistics kept in the Swedish Statistics (SCB) database are collected by Tullverket (Swedish Customs and Excise), and there is no record of *country of origin* for imported food since 1995, only the last *country of port*. Since Sweden joined the EU in 1995, interpreting trade statistics and trying to establish where imported foods originate on a national and aggregated level has become impossible. Country of export may not be the country where the food was produced. Therefore statistics on origin of imported food should be interpreted with care. This applies especially to foodstuffs such as tropical fruits, stimulant crops and soya products, which arrive by ship at large ports in the EU and then are sent on to Sweden. When Swedish food trade is described below, import partners are not country of origin but country of port in the statistics. However, often they happen to be the country of origin as well as country of port.

Sweden's major import partners for agricultural products and food in 2000 were Denmark, the Netherlands, Norway and Germany. These four countries were responsible for about half the import value. The main import partners outside Europe for the same year were the USA (coarse grains, rice, fruit), Brazil (cattle meat, animal fodder), Costa Rica (fruit), Colombia (coffee), Panama (fruit) and Thailand (rice). On the whole, the largest food imports in value were wine, whole salmon, unroasted coffee beans, cheese and bananas.

Sweden exports approximately half as much food, in value, as it imports. A major proportion of Swedish food exports, 59% of value in 2000, was to the EU market. The USA was the largest country of export outside the EU, followed by Norway. Nation-wise, USA was also the top export country, followed by Denmark, Finland, Norway and Germany. The largest export during 2000 was salmon and other fish, mostly re-exported after import from Norway. Other important export products to the EU are processed foods like baked goods, chocolate, cheese, oils, margarine and vodka. The largest food export to countries outside the EU for the same year was vodka, which corresponded to more than a quarter of the exports to these countries. The second largest food export was barley. Other important food exports were roasted coffee (USA), margarine (Russia, Poland), chocolate (Norway) and baked goods (Norway).

Trends affecting future food supply

Researchers and policy makers continue to struggle with the same equation: how to feed a growing population (Kendall & Pimentel, 1994; Parikh & Painuly, 1994). Malthus was one of the early authors to illuminate the dilemma of feeding a growing population (Malthus, 1798). Some are more optimistic than others. Harris (1996) believes that the discussion of world agriculture futures has usually been framed in a Malthusian context, with technology optimists on one hand opposing neo-Malthusian pessimists on the other.

Since Malthus in the 19th century, and on to Lester Brown and the Worldwatch Instituet's 'State of the World' today, much focus has been on population growth and the availability of agricultural land. However, in recent years there has been an increased discussion of indirect factors such as ecosystem services (Daily, 1997b), ecosystem health and resilience (*e.g.* Holling, (2001) and their importance for ecosystems in sustaining humankind. It has become more apparent that it is more to it than what first meets the eye. Its what we *don't* see that could be the most determining issue for our future food security.

My perspective is that success in meeting future needs will depend on the following factors, however not listed in specific order of importance:

- Changes in **consumption patterns**
- Quality and amount of **agricultural land**
- **Population growth**
- **Climate change**
- Availability of non-renewable **resources**
- **Technological** change
- **Global political change** affecting economic power and trade
- **Ecosystem integrity** and ability to generate resilience and ecosystem services to buffer disturbances and degradation

In this thesis I focus on a few of these factors more than others, but that does not mean that some other factors may not be equally, or even more, important for the future food system. One has to bear in mind that the food system is a self-organising system and hence unpredictable. Trends may take different turns and one factor may suddenly become more influential than another, while all trends occur at the same time, reinforcing or hindering each other.

Food consumption patterns

Food consumption patterns are repeated arrangements of food consumption that can be observed in a group of people. They depend on several factors, such as personal preferences, culture and tradition, personal finances, health and nutritional requirements, and availability. Personal preferences can be both genetical and environmental, and they often change with age (Logue, 1986).

One of the most revealing pieces of information about an animal species, other than its taxonomic position, is its diet. This has major implications for its pattern of life and abilities. *Homo sapiens* is an omnivorous, generalist species. Around the world, almost anything that has a nutritional value is consumed by humans. The advantage of being a generalist is that there are more ways to obtain adequate nutrition, and this provides more resilience in the presence of other species competing for some of the same foods. However, generalists risk nutritional imbalances since they happen upon many potential foods that have nutritive value, but are not complete nutrients. Appropriate combinations of foods must then be selected (Rozin, 1999).

More than 10 000 years ago, humans sustained on a diet drawn from a large variety of plants and animals and were mostly reliant on what could be found in nature, through hunting and gathering. On a time scale, *Homo sapiens* has depended for its sustenance on hunting and gathering for more than 99% of its evolutionary history. However, population has increased more than one thousand-fold since then. From a population perspective, it is estimated that 12% of the 80 billion humans who have ever lived have done so by hunting and gathering (Evans, 1998). Since our hunting and gathering days, we have gradually domesticated animal and plant species and become more and more dependent on a specific area for our food supply. Arable land has become the source for over 90% of the food we consume and the variety of animals and plants consumed has decreased. Today the world's population largely depends on thirty plant species, with four crops (wheat, rice, maize and potatoes) contributing more tonnage to total world consumption than the next twenty-six species combined (Harlan, 1976). Wheat, today the most commonly grown grain, has been grown in the Middle East for over 10 000 years, and in Sweden for about half that time, since the early Stone Age (Fogelfors, 1997). About the same time spans are valid for our first domestic animals (after dogs), sheep, goats, aurochs (early cattle) and pigs being domesticated in Asia 10 000 years ago and introduced to Sweden a little more than 6 000 years ago (Björnhag, 1997).

Diet matters

Diets for better health are being designed and discussed continuously in society and healthcare. On an almost daily basis, we are given recommendations on what to eat to stay healthy or lose weight. Diets for a better environment are less often discussed. However, some nutritional scientists have begun to critically reflect on the sustainability of agriculture as practised today, and the link to what we eat and how resources are used (Gussow & Clancy, 1986; Herrin & Gussow, 1989; Gussow, 1999; Lindeskog & Dahlin, 1999).

Diet matters for environmental sustainability (Goodland, 1997), and changes in our diet also change resource use. Throughout the world there appears to be a direct link between dietary preferences, agricultural production and environmental degradation (Gussow & Clancy, 1986; Herrin & Gussow, 1989; Kendall & Pimentel, 1994; Pensel, 1997; Carlsson-Kanyama, 1998b; Schneeman, 2001;

Gerbens-Leenes & Nonhebel, 2002; Carlsson-Kanyama, Ekstrom & Shanahan, 2003; Pimentel, 2003; Reijnders & Soret, 2003). Gerbens-Leenes, Nonhebel & Ivens (2002) even claim that dietary choices and consumption patterns may be more influential on resource use than population growth in the future. Gussow & Clancy (1986) believe that a change to a more sustainable food system may well start with the consumers making the right choices, since they are the final arbiter of the food system. A way to make food consumption more sustainable is by starting with dietary guidelines, which help nutritionists teach consumers about healthy eating. Gussow & Clancy (1986) propose that nutritionists at the same time can help consumers eat sustainable by promoting *sustainable dietary guidelines*.

Scepticism has been directed particularly at supporting the increased demand for animal products in diets. Reijnders and Soret (2003) have evaluated the environmental impact of different dietary protein choices (vegetarian and non-vegetarian) by using data from several published studies. Their evaluation of processed protein food, based on soya beans and meat, suggests that the environmental burden of vegetarian foods is usually relatively low, even when production and processing are considered. See Table 1 for a summary of the differences between meat protein and protein based on soya bean.

Table 1. Relative environmentally relevant differences between meat protein and a processed protein food based on soya beans

Environmental impact	Soya bean based protein	Meat protein
Land requirement	1	6-17
Water requirement	1	4.4-26
Fossil fuel requirement	1	6-20
Phosphate rock requirement	1	7

(Reijnders & Soret, 2003)

Then again, it must be taken into consideration that there are many benefits to animal production. They have functions in the agroecological systems, contributing to the system with positive feed-back. In some agricultural systems, animals play important roles in *e.g.* traction, weed control, and maintaining and increasing soil fertility through the return of manure. Grazing cattle also maintain and increase the biodiversity of the landscape. Some animal species can efficiently convert foods that we humans cannot or will not eat into high quality foods such as meats and dairy products. Animals can eat by-products from agricultural production (*e.g.* straw) and the food industry (*e.g.* oil cakes and bagass), and cereals (oats, barley, wheat, rye, *etc.*) that do not meet the standards set by bread, pasta, brewing/distilling or other food industries. Livestock may be considered as an upgrading system (Nonhebel, 2004). Animals can also graze land not suitable for cropping (Schneeman, 2001).

We must also remember that there is currently a global imbalance between malnutrition and overconsumption. It may be true that we in the North eat more protein food than we need, and too much of it animal-based which further burdens the scale. However, there are large populations today that need to *increase* their protein intake since they are undernourished and live greatly impaired lives because of that. Large populations in *e.g.* sub-Saharan Africa do not get enough nourishment to stay healthy, go to school or work with food production and development of their countries (Bradford, 1999). This means that as we strive for a world with decreased poverty, we will most likely also see, at least initially, an increase in more resource-demanding consumption patterns. The concept of a good diet must incorporate more than nutrition and environmental sustainability. Just and fair trade and social sustainability are also important aspects of a sustainable diet commensurate with sustainable development on a global level.

Consumption pattern trends

Increased economic wealth, migration, travel and adoption of food cultures from other parts of the globe, changed health recommendations, fashion trends and changes in lifestyle are all examples of factors that can change consumption patterns. Today we see a decline in traditional cooking in countries in the North, with trends moving towards consumption of a wider range of ready-made foodstuffs (Tansey & Worsley, 1995).

York and Gossard (2004) found that ecological conditions in a nation, such as resource availability and climate, influence the consumption of both meat and fish. Per capita, nations in temperate regions consume nearly 19 kg per year more meat than subarctic/arctic regions and 11 kg per year more than tropical regions, after correction for other factors. Nations with highly urbanized populations consume more meat per capita than those with less urbanized populations. The availability of land also has a significant influence on meat consumption; nations with more land per capita consume more meat per capita, although this is becoming less of a significant factor as globalisation and increasing trade continue to separate people from possible constraints to their local environments. In addition, economic development influence the consumption of both meat and fish, although differently in different parts of the world. Western nations have a tendency to consume more meat as their economies develop, and Asian nations have a stronger tendency to consume fish at higher rates as their economies develop.

Food consumption in Sweden

A national survey of food and nutrient intake in the Swedish population was carried out in 1989. The main sources of energy and protein for the average person living in Sweden were dairy products, such as milk, various fermented milk products and cheese, followed by cereal products, meat and meat products and edible fats. The main sources of fats were edible fats, followed by cheese, dairy, meat and meat products (Statens livsmedelsverk, 1994). Swedish consumption of various milk products, such as butter, milk and yoghurt is the second highest in the EU after Finland (Statens jordbruksverk, 2004). Since the survey in 1989, meat consumption in Sweden has increased by 33% (Statens jordbruksverk, 2004).

The 1989 survey revealed clear differences between various age and gender groups regarding food intake. Children drank more milk and ate more pasta and foods containing sugar than adults. Adults and adolescents ate more potatoes, bread, meat and cheese than children. Men ate more potatoes, spreads, meat and fish and drank more milk than women. Level of education also affected food intake, especially among men. Men with a university education used less spreads on sandwiches, ate less potatoes but more vegetables, fruit, pasta and fish than men with less education. Well-educated women ate more vegetables, cheese and pasta but less potatoes than women with low education. Some regional differences in food and nutrient intake were observed. The intake of fruit and vegetables tended to be lower in northern Sweden than in the Stockholm area, while the consumption of milk and spreads was higher (Statens livsmedelsverk, 1994).

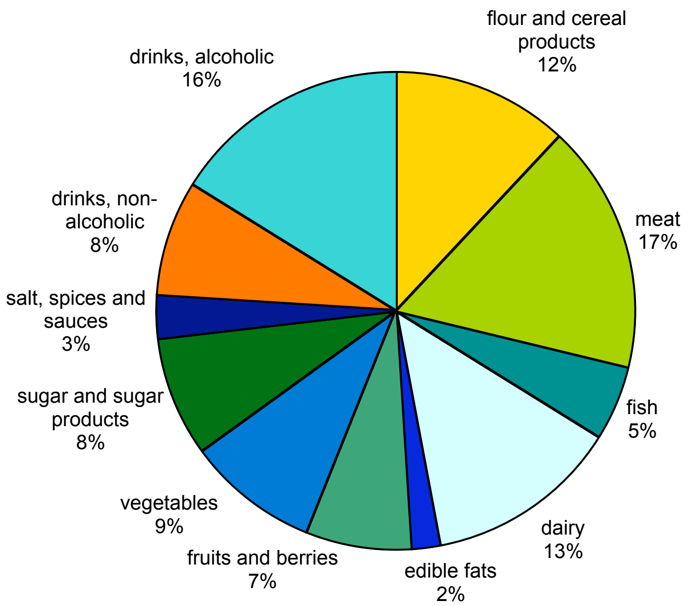

Figure 1. Household expenditure on food by consumers in Sweden 2001, according to National Accounts (Statistics Sweden, 2005).

Fifteen percent of average Swedish household expenditure went on food in 2001. The average consumer in Sweden spent 35% of the money spent on food on various animal products, such as meat, dairy products and fish. Sixteen percent was spent on vegetables, fruits and berries, and 12% on cereal products such as flour, breads, grain and baked goods. More than a third of food expenditure, 35%, was spent on food considered to have little or no nutritional value, such as alcoholic drinks, non-alcoholic drinks such as coffee, tea and juices, sugar products and spices (Statistics Sweden, 2005).

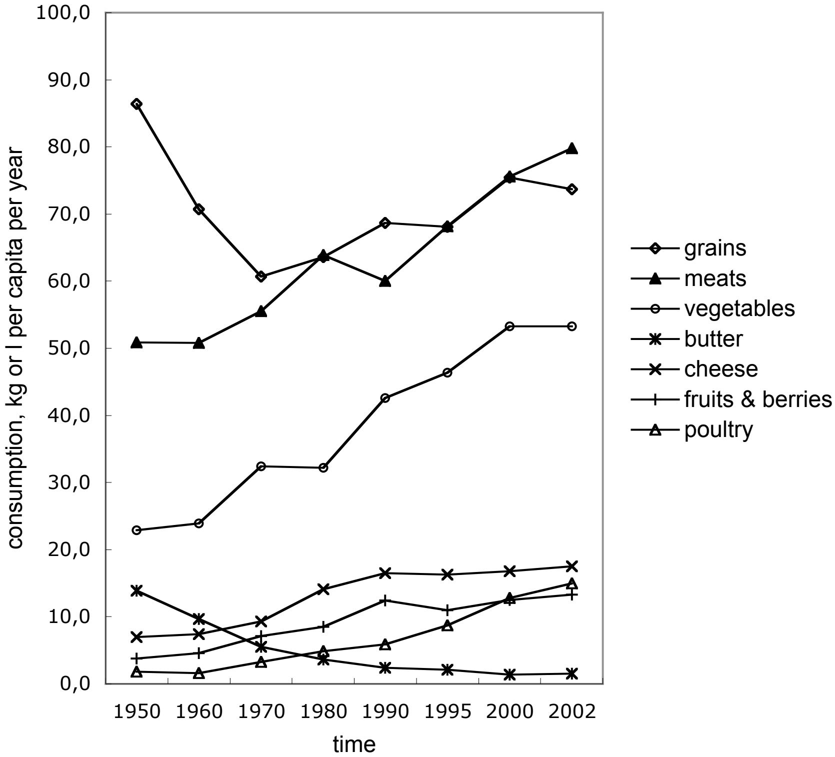

Figure 2. Total consumption of certain food products in Sweden 1950-2002 in kg or l per capita per year (Statens jordbruksverk, 2004). Meats include all meats, also poultry.

Some of the more noteworthy changes in consumption pattern trends in Sweden from 1950 to 2002 are shown in Figure 2. Poultry consumption has increased since 1950 by a massive 733%, from 1.8 kg to 15 kg per capita and year. Fruit and berry consumption has increased by 250%, cheese by 150%, vegetables by 133% and meat consumption in Sweden has increased by 57%. Consumption of cereal products first decreased by 30% up to 1970, to increase again by 2002 so that the total decrease was 15%. Consumption of butter has decreased by almost 90% (Statens jordbruksverk, 2004).

Even though meat consumption is increasing in Sweden, it is still amongst the lowest in Europe compared to other EU countries (Table 2). Consumption of poultry is the lowest in the comparison. Consumption of dairy products, such as various milk products (fermented milks, buttermilks, yoghurts, etc.) and cheese, that play an important role in our nutrient intake as described earlier, are amongst the highest.

Table 2. Consumption of animal food products in EU-countries and in the USA in 1997 (kg per capita). Bold indicates highest consumption in comparison, and underlined the lowest (Statens jordbruksverk, 2000; USDA, 2005)

	Meat	whereof				Products from fresh milk	Cheese	Eggs
		Beef and veal	Pork	Sheep	Poultry			
Sweden	68	19	36	1	9	150	16	12
Bene-Lux	95	21	43	2	22	84	15	14
Denmark	101	20	57	1	18	141	15	**15**
Finland	66	19	32	0,4	11	**197**	15	10
France	107	27	35	5	24	101	**23**	-
Greece	88	23	25	**14**	20	67	**23**	-
Ireland	108	17	39	9	**32**	177	6	7
Italy	88	24	34	2	19	72	19	-
Netherlands	83	18	41	1	21	128	15	13
Portugal	94	15	39	4	28	106	8	8
Spain	**118**	14	**60**	6	27	132	8	**15**
United Kingdom	77	17	23	6	26	128	9	11
Germany	90	15	53	1	15	88	19	14
Austria	95	20	55	1	17	95	15	14
EU15	93	19	42	4	20	105	16	13
USA[1]	80	**29**	21	0,4	29	96	13	14

[1] USDA Agricultural statistics 2001

The average food consumer in Sweden eats well from a nutritional point of view. Children in pre-school and school are served free lunch every day. Few are malnourished in Sweden. The 1989 dietary survey showed that average intake of vitamins was generally above the recommended levels, as was that of most minerals with the exception of selenium among adults, and iron and zinc among women of childbearing age (Statens livsmedelsverk, 1994).

Agricultural land use

About one third of the earth's surface is covered by land and two thirds by water. Of the land area, a little more than a third is agricultural land, and of that agricultural land almost a third is arable and two thirds are pasture land. Forests cover roughly another third of the global land area. Nine percent of the global land area has been claimed by urban sprawl, such as cities and roads. The remaining 23% is mountain, deserts and tundra. These areas are too steep, too wet, too dry, or too cold to be financially viable for agriculture today (Buringh, 1989; Pimentel *et al.*, 1999).

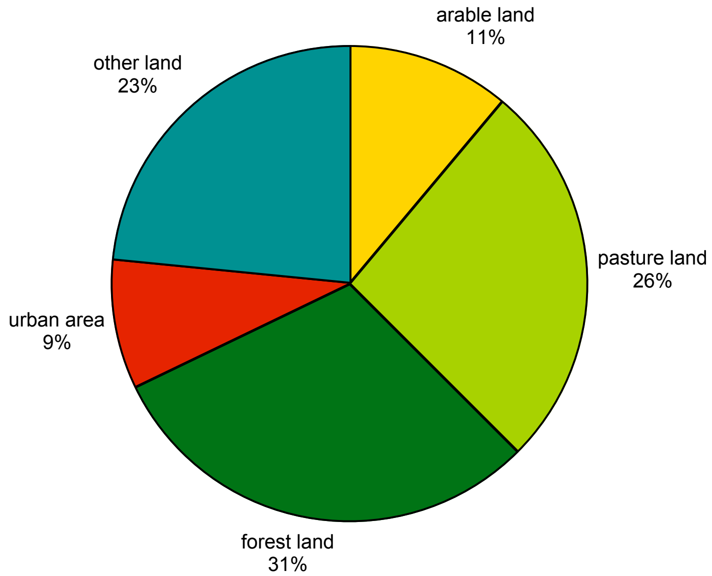

Figure 3. Global land use (Buringh, 1989; Pimentel *et al.*, 1999)

Arable land (crop land) and pasture land (grazing land) together make up the available agricultural land. Today, agricultural land amounts to around 5 billion hectares, whereof arable land constitutes about 1.4 billion hectares (FAOSTAT, 2003). Arable land is the land that is tilled. Pasture land is not considered to be suitable or possible to cultivate, and is instead mostly grazed. On the global scale, arable land produces about 93% of our food, the other 7% coming from pasture land (6%) and from marine sources (1%) (Gaull & Goldberg, 1993; Pimentel & Pimentel, 1999). With a population of 6.2 billion people in 2002, arable land was 0.23 ha per capita (FAOSTAT, 2003; UNPD, 2005). In 1959, George Borgström calculated it to be 0.48 hectares per capita, *i.e.* more than twice as much (Borgström, 1973). If population growth follows UNPD's projections, and available arable land area stays the same, it would be less than 0.18 ha per capita in 2025. It should also be noted that the urban area is almost as large as the arable land and that this area is often appropriated arable land, *i.e.* urban sprawl has often happened on fertile land close to where humans have chosen to settle.

The total land area of Sweden is 41.1 million ha, whereof a major proportion is mountain and forest area not suited for cultivation. In the period 1997-2000, Sweden had on average an agricultural area of 3.2 million ha, with 2.8 million ha being arable land and more than 0.4 million ha permanent pasture land. This corresponds to 0.31 ha of arable land per capita in Sweden, compared to the world average of 0.23 ha per capita, and 0.05 ha of pasture land not suited for cultivation, compared to the world average of 0.58 ha per capita (FAOSTAT, 2003). There has been a decrease in agricultural land in Sweden between 1951-1992. About 20% of Swedish agricultural land has been removed from production, most of it has been overgrown with brush, reforested or urbanised (Björklund, Limburg & Rydberg, 1999). The conditions for crop production in Sweden display great differences between the north and south of the country. More than 60% of arable land is found on the fertile plains in the southern part of the country. Crop production in Sweden is strongly dominated by cereals and ley, corresponding to 39% and 30% of the agricultural land in Sweden respectively (Statistics Sweden, 2001). Ley is arable land sown with various grass and clover crops for production of roughage (*e.g.* hay and silage) and grazing.

Trends in global agricultural land availability

People are already today competing for ecological space, *i.e.* land for food production, freshwater for irrigation and drinking water, and land for firewood production. Land use and land shortages cause people to migrate, which can lead to tensions and ultimately refugee camps, diseases and war. Land and water resources are declining both in quantity and in quality due to factors such as competition with industrial and urban demands, degradation and pollution (FAO, 1996). Until now, new agricultural land has been 'found' at almost the same pace as land has been lost. FAO statistics show no significant loss of total arable land in the last 40 years, from 1961 to 2000 (FAOSTAT, 2003). On the other hand, one must remember to distinguish between land totally degraded and lost for production, and land partially degraded but still in the agricultural system with lower productivity.

IFPRI (2002) estimates that in the future arable land could, theoretically, be doubled but acknowledges that there are potential problems due to competition for land for other purposes and difficulties with freshwater supplies for irrigation. If more area can be taken into production, this new land may require more resources not only for irrigation, but for increased fertilisation and mechanical work, *etc.* to produce the same volume of crops (IBSRAM, 2001). Other researchers claim that most of the world's suitable land is already under cultivation (Chambers, Simmons & Wackernagel, 2000), and the environmental costs of converting remaining forest, grassland and wetland habitats to arable land are well recognised. Even if such lands were converted to agricultural use, much of the remaining soil would be less productive and more fragile and thus its contribution to future world food production would likely be limited. Agricultural land use and productivity are subject to various constraints, such as soil degradation and loss of ecosystem functions.

Soil degradation

Soil degradation is loss of function of the land. It reduces the capacity of the land to provide goods. Causes of soil degradation include natural processes and human activities, the latter being by far the most significant (Rossiter, 2001).

There are several types of land degradation. *Soil erosion* is mostly caused by wind and water and can vary greatly in severity, causing lower potential yields on one end of the scale, and whole land areas to disappear on the other. *Salinisation* is an increase in salt in the soil, often due to poor irrigation management. *Soil fertility exhaustion* reduces the potential yield due to the decreased ability of soils to hold water, nutrients and maintain structure. *Urban land use* is an extreme form of land degradation where the land is lost entirely for food production. These are unfortunaltely often very fertile soils, since a lot of urban areas and cities have grown from settlements close to river banks and surrounding fertile land. *Desertification* does not refer to the moving forward of existing deserts alone, but to the formation, expansion or intensification of degraded patches of soil.

Large areas of arable land have been degraded in quality, even if not in quantity. Degradation in quality lowers the efficiency of use of inputs and increases risk. More weeding is required, replanting or reseeding is sometimes needed, fertilisers are lost in runoff, products are of lower quality and crops fail in some years due to degradation in land quality. Larger quantities of inputs such as fertilisers, pesticides and irrigation are needed to compensate (Langdale *et al*., 1992). Not only are these inputs fossil-energy dependent, but they also harm human health and pollute the environment (Pimentel *et al*., 1999; IBSRAM, 2001). When productivity decreases, more land area has to be taken into production.

Table 3 shows average annual rates of change in percent of land lost and found, with data from 40 years between 1960 and 2000 produced by IBSRAM (2001). *Degradation* here means arable land lost entirely for agricultural practices. *Urban sprawl* is arable land becoming occupied by infrastructure, *e.g.* cities and roads covering more and more ground. *Deforestation and clearing* is new area taken into agricultural production, *i.e.* additional area. Despite significant losses there has, according to this study, been a *net expansion* in hectares when all things are considered. The author warns that degradation is far from uniform in any region, and averages must be interpreted with care. For example, areas degraded partially but still in production are not included, and degradation can be hidden by the application of extra inputs (IBSRAM, 2001). However, the expansion of new areas taken into production could be a response to other areas having lost productivity.

Table 3. Average rates of change per year in percent of agricultural land 1960-2000 (AFR = Africa south of Sahara, EAP = East and South East Asia, LAC = Latin America and the Carribean, MENA = Middle East and North Africa, and SA = South Asia.)

	World	AFR	EAP	LAC	MENA	SA
Degradation (–)	0.5	0.7	0.6	1.0	0.6	0.6
Urban sprawl (–)	0.1	0.05	0.15	0.1	0.1	0.1
Deforestation and clearing (+)	0.9	1.55	0.95	2.5	1.2	0.9
Net expansion (+)	0.3	0.8	0.2	1.4	0.5	0.25

(IBSRAM, 2001)

Human-induced soil degradation is assessed through Global Assessment of the Status of Human-induced Soil Degradation (GLASOD) (Oldeman, Hakkeling &

Sombroek, 1990). In this assessment, soil degradation is classified in different degrees of severity; light, moderate, strong and extreme. A light degree of soil degradation implies somewhat reduced productivity, but is manageable in the local farming system. A moderate degree of soil degradation implies greatly reduced productivity, and major measures are required for restoration. Strongly degraded soils are no longer reclaimable at farm level and are virtually lost. Major engineering works, and international assistance if in a low-income country, are required for restoration. Extremely degraded soils are considered unreclaimable and beyond restoration.

Loss of ecosystem services

We are dependent on the goods and services of our ecosystems for our survival. Ecosystem services are life-supportive services provided by natural ecosystems, as well as by agro-ecosystems and other landscapes with mixed patterns of human use (Daily, 1997a; MA, 2005). The services include *provisioning services* such as food, water, timber and fibre; *regulating services* that affect climate, floods, disease, waste, and water quality, *cultural services* that provide recreational, aestetic, and spiritual benefits; and *supporting services* such as soil formation, photosynthesis, and nutrient cycling (MA, 2005).

Between 1960 and 2000, the demand for ecosystem services grew significantly as world population doubled to 6 billion people and the global economy increased more than sixfold. The growing demand for these ecosystem services was met both by consuming an increasing fraction of the available supply (such as fresh water and fish) and by raising the production of some services, such as crops and livestock. However, actions to increase one ecosystem service often cause the degradation of other services. For example, because actions to increase food production typically involve increased use of fresh water and fertilisers or expansion of the arable are, these same actions often degrade other ecosystem services, including reducing the availability of water for other uses, degrading water quality, reducing biodiversity, and decreasing forest cover which in turn may lead to the loss of forest products and the release of greenhouse gases (MA, 2005).

Regulating ecosystem services relevant for food production, such as pest regulation, regulation of climate and erosion and pollination are declining according to the assessment made by Millennium Ecosystem Assessment (2005). Biodiversity is diversity in ecosystems, diversity of species and genetic diversity within a species. Tilman (1997) means that many aspects of the stability, functioning and sustainability of ecosystems depend on biodiversity. The wide range of species and populations secure the biodiversity, generating most ecosystem services important especially for agricultural production, providing pollination and natural pest enemies. Losses of pollinators have been reported on every continent, except Antarctica, according to a report by the World Resource Institute (2000). 'The consequences of continued pollinator declines could include billions of dollars in reduced harvests, cascades of plant and animal extinction, and a less stable food supply' (WRI, 2000), according to the same report.

Changes in human population and demography

The world population is projected to continue its increase, to more than 9 billion by 2050 (UNPD, 2005). Populations will grow mainly in countries in the South and in the USA. However, Sweden's population, as wall as that of Europe, is predicted to decrease. The global population growth means that the food production increase needs to be more than proportional to population growth so as to provide all with an adequate diet (Kendall & Pimentel, 1994). In the last decade, it seemed that the proportion of starving people was decreasing and more people were adequately fed than ever before. However, statistics from 2004 show a reverse in this trend. FAO estimates that 852 million people in the world were undernourished in the period 2000- 2002. Hopeful decreasing trends during the first half of the 1990s turned into an increase in starving people of around 4 million per year in the last years of the decade (FAO, 2004). Meeting the millennium goal of FAO/UN to halve the population of starving people by 2015 seems out of reach today.

More people are being born and people are also living longer. Urbanisation is increasing, in turn extending the food chain. Now the system is being affected not only by how many people we need to feed in the future, but also where people live. Urban people buy food produced far away and transported to cities from rural areas and all parts of the globe. Centralised buying by supermarket chains can lead to smaller producers being squeezed out of the market as they are unable to produce the quantities required (Tansey & Worsley, 1995). Furthermore, global trends for increased demand for meat, dairy products and fruits and reduced demand for cereals are presumably associated with urban expansion and the prevailing lifestyle within them (SIWI & IWMI, 2004). These trends of urbanisation may have an adverse effect on the sustainability of the food system and on the people living in the South.

Changes in available resources

Contemporary agriculture and food production is high in resource use, especially non-renewable resources (Johansson, Doherty & Rydberg, 2000). The availablility of these resources on the globe are decreasing. Not only are non-renewable resource decreasing, but by each year more effort is needed to appropriate what remains (Odum & Odum, 2001). Scientists differ in opinion on when these resources may end. While the increasing needs for agricultural products and non-renewable resources are difficult to quantify, there is no doubt that they will be large in the future.

Fossil fuels, *i.e.* oil, gas and coal, account for a large portion of global energy use These fuels were formed over millions of years, million years ago, and are finite and considered non-renewable since they take so long to form. Fossil fuel is used for most of the traction work in agriculture and most transportation in the food system. It is also used when mining phosphate rock, when producing nitrogen fertilisers, for irrigation and much more crucial work in the food system. In fact, most fuels used in the food system are fossil-based, and thus a decrease in these resources will have a huge impact on our future food security. Fossil fuel resources are reported as *estimated ultimately recoverable* (EUR) global oil, the total amount of oil that can eventually be pumped from the earth. Oil experts estimate that EUR oil reserves lie within the range 1 800 to 2 200 billion barrels (MacKenzie, 2000). As of recently, the world had consumed about 860 billion barrels of these ultimately recoverable reserves. Assuming a growth in demand of about 2%, it has been estimated that these reserves will (pessimistically) peak in 2007 or (optimistically) peak around 2013 (MacKenzie, 2000).

Phosphate rock, which today is the main source of phosphate fertilisers, is a finite mineral. Phosphate is vital for crop production. There is a link between phosphate rock and global food supply. It is predicted that the un-mined rock may last for between 200 and 1200 years (Louis, 1993). Phosphate is the focus of much research and development of new systems to promote recycling of phosphate in human wastes. Much of the phosphates that enter the food system end up in organic wastes and sewage sludge, and some in household composts. Many efforts are being made to find hygienic solutions to recycle this phosphorus back into the agricultural production system.

Food production is a highly water-consuming activity, by far the most water-consuming of all human activities. Huge volumes of water are transformed into vapour during the plant production process, *e.g*. beween 500 and 3 000 litres of water are required to produce one kilogram of grain (SIWI & IWMI, 2004). Depending on diet, each person is responsible for the conversion of 2 000 to 5 000 litres of water to vapour each day (SIWI & IWMI, 2004). This is significantly more than the average 2 to 5 litres of drinking water, or average household requirements of between 100 to 500 litres per person per day for cooking, laundry, showers *etc*. in countries in the North (SIWI & IWMI, 2004). If the world is facing a future of water shortages, then it is also facing a future of food shortages. Irrigation is vital to global food production. Abouts 16% of the world's arable land is under irrigation, but this area contributes about one-third of crop production, yielding about 2.5 times as much per hectare as non-irrigated land.

Technology

Food production has gone through a number of technological changes since the hunter-gatherer stage. Only a few crucial technological changes will be mentioned here however. Mechanisation of agriculture, development of fertilisers, new crop varieties, irrigation and development of weed control products have helped in increasing agricultural production. Starting in the 1960s, scientists developed modern high-yielding crop varieties of wheat, maize and rice and released them to farmers in Latin America and Asia. The success of these crops, increasing global yields in an unprecedented way, was characterised as the *green revolution* (Evenson & Gollin, 2003). However, it also meant intensified use of inputs. Scientists have now taken it further with biotechnicqe, developing Genetically modified organisms (GMOs) even better suited to fit in to the industrialised agricultural systems.

Food technology, such as canning and refrigeration of food, has historically had a huge impact on our food security. Refrigeration made it possible to transport perishable foods such as eggs, meat and butter to Europe from distant sources, such as Australia, New Zealand and Argentina, creating a 'cold tunnel through the heat belt of the tropics' to use the words of Georg Borgström (1973). 'Human population growth may have been aided by medical measures taken in the second half of the 19^{th} century, but these would have been of no avail without the successful efforts to feed the growing numbers of Europeans who survived' (Borgström, 1973). In the future we may see an increase in food technology inventions, with 'intelligent packaging' reducing food loss. New techniques to increase shelf-life of food will enable an even more global food system allowing for longer transportation.

A large proportion of harvests in countries in the South is lost due to spoilage, while in food production systems in the North, there is also some loss of food. There is a large potential to make significant savings of food and resources in the future if these losses can be decreased.

Methodological framework

Two apples may have the same energy and nutrient content, they may produce the same waste, they may even look and taste the same. But an apple from New Zealand and an apple from Sweden come from two different systems, and therefore have different impacts on the environment when eaten in Sweden. An apple is not just an apple, it is part of something bigger, a sequence of circumstances, a system of many parts and processes that are connected in many different ways, all parts and events playing a role of their own. A holistic approach is needed to understand the impacts of eating the apple. The holistic approach used throughout this thesis is based on the following methods and approaches.

The *foodprint* – an agroecological footprint

In this thesis I investigate the food system supporting food consumption in Sweden. It is an agroecological study, using the broader definition of agroecology, *i.e.* the whole food system is under scrutiny (Francis *et al.*, 2003). While the term 'food system' is common, the concept of a system is often used loosely according to Sobal, Khan & Bisogni (1998), and is not always linked with systems theory. The food system is often described linearly, simply as a chain of events from agriculture, through processing, marketing and distribution, on to the end consumer. In this study the food system is considered in a holistic way, respecting all contributions, by man and nature, that support food consumption.

Different methodologies have different abilities to capture the system and how it functions. Below I describe the different methods and approaches I chose to use, when developing my *foodprint* in this thesis. I was inspired by the foodshed approach to ask where our food is coming from, by ecological footprinting to calculate area appropriated and by emergy analysis to capture resource use and environmental impact. I call my approach a *foodprint* approach, *i.e.* the footprint of our food consumption. (The word *foodprint* is in italics through our the thesis, making it easier to distinguish from the term footprint as in ecological footprint (EF).)

I do this in three steps, gradually broadening the scope. In the first study, *Agricultural area for food consumption in Sweden 1997-2000 – A study of the direct and semi-direct areas*, I calculate a footprint including the directly and semi-directly used agricultural area appropriated for food consumed in Sweden 1997-2000. In the second study, *The Swedish foodprint – Directly and indirectly appropriated area for food consumption in Sweden 1997-2000*, I broaden the footprint to include indirectly used areas appropriated for ecosystem services and new area appropriated due to land degraded. In the third study, *Emergy synthesis and emergy footprint of food consumption in Sweden 1996*, I broaden the system boundary even further to include the entire foodsystem and a more comprehensive analysis of indirect resource use. I continue by translating the emergy synthesis of Swedish food consumption into a footprint, an *emergy footprint*. For each study, the footprint supporting Swedish food consumption (the Swedish food system) is enlarged. incorporating more aspects. Much of this due to a broadening of, not necessarily the direct systems boundaries (the focus is always on the food system supporting food consumption in Sweden), but the *window of attention* and the amount of environmental support that the different methodologies are able to incorporate.

Systems approach and the notion of self-organisation

A key concept in systems thinking is the notion that a system's components interact through one or several processes, and they are dependent on each other. It is a holistic approach, stating that the whole becomes more than the sum of the parts when there are interactions (Odum, 1994). Instead of cutting a studied system into pieces, systems theory concentrates on the system as a whole, and on processes occurring inside the system. Many of the problems we are faced with are interconnected and cannot be understood in isolation. In fact, almost everything in the world interacts with everything. Obviously, we then need to take a holistic approach to understand and manage problems in a systemic way. The properties of a system may be summarised in the phrase 'behaviour as a whole in response to stimuli to any part'. A collection of unrelated items does not constitute a system (Spedding, 1979).

According to Capra (1982) systems theory recognises the inseparable web of relationships and the concept of self-organisation. The conception of self-organisation provides a framework for understanding how systems grow and develop over time that is inclusive of internal constraints, and considers thermodynamic limits and their relation to the ability of a system to build and maintain structure, organisation and distance from equilibrium (Müller &Nielsen, 2000). "It is important to state that while the concept of self-organisation stems from the natural sciences, it does not deny human agency (Kay *et al.*, 1999) and can be used to interpret social phenomena, such as the global food system. Humans cannot be separated from the system.

Systems ecology developed by HT Odum

Lotka (1922) states in the *maximum power principle* " … that in the struggle for existence, the advantage must go to those organisms whose energy-capturing devices are most efficient in directing available energy into channels favourable to the preservation for the species." The maximum power principle states that systems self-organise to develop the most useful work with inflowing energy sources, by reinforcing productive processes and overcoming limitations through system organisation and re-organisation. These systems that do well at this will prevail in competition with others (Brown & Ulgiati, 1999).

This principle is a fundamental theoretical concept underlying systems ecology and emergy synthesis, see following chapter on this synthesis. Inspired by the maximum power principle, Odum (1996) pronounced the *maximum empower principle* as follows:

> "At all scales, systems prevail through system organization that first, develop the most useful work with inflowing emergy sources by reinforcing productive processes and overcoming limitations and second by increasing the efficiency of useful work."

Processes that waste energy, that "dissipate energy without useful contribution to increasing inflowing emergy are not reinforcing, and thus cannot compete with systems that use inflowing emergy in self-reinforcing ways." (Brown *et al.*, 2000)

Fundamentals of emergy synthesis are based in systems ecology principles, thermodynamic laws and recognition of biophysical limits to conversion processes. The postulate of self-organisation states that complex adaptive systems yield hierarchical designs that generate useful energy transformations (e.g., Odum 1984). Hierarchies produce structures and patterns that reinforce lower level processes, enhancing system performance. Thus, products and processes resultant from nested interactions, have contributions or impacts commensurate with their developmental history. Emergy, as a donor-based measure of direct and indirect resources used to generate or maintain a product or service, equates inputs and use as utility metrics (Odum 1996).

Agroecology

Agroecology is described in different ways in the literature, ranging from the science of agriculture and ecology (Altieri, 1987; Gliessman, 1990), and extending to the ecology of the entire food systems (Francis *et al.*, 2003). In order to appreciate and embrace the 'wholeness and connectivity of the food system', Francis *et al.* (2003) propose a definition of agroecology that 'expands our thinking beyond production practices and immediate environmental impacts at the farm level'. When we focus on the agricultural production alone, we fail to integrate the large resource use in processing, transportation and marketing steps of food production that bring the food to the kitchen table (Johansson, Doherty & Rydberg, 2000), which is ultimately an important goal for most agriculture today. However, Francis & Rickerl (2004) point out that it is too early to determine if this expanded definition of agroecology, including the entire food system, will become common in research and education. Nevertheless, I have adopted this broader definition in my research. As I have chosen to understand agroecology, it is a science with a systems approach, where interdisciplinary and holistic methods are used to study questions of food production and consumption at different levels of spatial scale. I understand agroecology to be *food systems thinking*.

Foodshed approach

One way of understanding food systems is by viewing them as foodsheds. The term foodshed was constructed to facilitate critical thought on the origin of our food. More concretely, foodshed analysis means answering the question: Where is our food coming from and how is it getting to us? The foodshed can serve as a 'conceptual and a methodological unit of analysis that provides a frame for action as well as for thought, measuring the flow and direction of these tributaries and documenting the many quantitative and qualitative transformations that food undergoes as it moves through time and space towards consumption (Kloppenburg, Hendrickson & Stevenson, 1996). Measuring flow and its quantitative and qualitative transformations is similar to the work done in an emergy synthesis, see separate section *Emergy synthesis*. The foodshed approach is food systems thinking, and can work for studying single foods or whole diets, on local or country level, depending on the focus of interest.

The metaphor of a 'foodshed', analogous to a watershed, was introduced by Hedden already in 1929 (*cit*. (Kloppenburg, Hendrickson & Stevenson, 1996), and was then re-introduced by Getz 60 years later (Getz, 1991). Getz promotes the analogy since it suggests the concept of the need to protect a source, here being the agricultural production and the producer. He says 'Common sense and past experience have shown us the wisdom of conserving a watershed area, and I believe we may be in the process of extending similar concepts to our food system'. Furthermore, Getz says that when trying to capture what a foodshed looks like today, with our complex and extended food system, we may get a 'rudimentary map of a foodshed (that) might cover the globe, or resemble an octopus with long tentacles extending out from a large urban supermarket to remote tropical plantations, vast Midwestern grain acreage, and California irrigated valleys of fruit and vegetables'. However, Getz continues, it may still be measurable, even if it is not 'mappable', and Getz suggests watching a border over which food is passing and documenting it (Getz, 1991).

The foodshed metaphor is often used when taking action towards eating more locally produced food. It is often used in the spirit of 'think globally, act (eat) locally'. Lezberg and Kloppenburg (1996) reject the idea of 'the market as the most appropriate arbiter of what food gets produced where and who gets to eat' With the foodshed concept they would like to present an alternative food security based on sustainable, self-reliant, local/regional food production.

Foodshed is easy to use as a metaphor, but there is no standardised methodology. It is more of a way of thinking about where our food is coming from.

Footprinting methodology

Footprinting is a way to translate activities into area. There are a few different approaches on how to do this. The most well-known may be the ecological footprint concept (EF) according to Wackernagel and Rees (1996). I will hereafter use the abbreviation EF when referring to the ecological footprint as described by them, to distinguish their concept from other footprinting methodology and calculations.

The EF concept has been designed to determine whether human loading is within global regeneration capacity, by estimating peoples' impact on the planet. Because people consume the products and services of nature, every person has an impact on the earth. This is not a problem as long as the load exerted by humans stays within global regeneration capacity, but often it does not (Wackernagel, Lewan & Borgström Hansson, 1999).

The ecological footprint tracks the energy and resource throughput of national economies and translates them into biologically productive areas necessary to produce these flows (Wackernagel *et al.*, 1999). Ecological footprint calculations are based on two assumptions:
1) Most of peoples' consumption and much of the waste they generate can be accounted for;
2) The biologically productive areas appropriated for production of this consumption and for assimilation of the waste can be calculated. (Wackernagel *et al.*, 1999)

In an ecological footprint the following six major components of biologically productive space are most commonly calculated: a) fossil energy land, b) arable land, c) pasture, d) forest, e) built-up area, and f) sea space (Wackernagel, Lewan & Borgström Hansson, 1999). Fossil energy land refers to the spatial impact of fossil fuel use and corresponds to the area needed for newly planted forest to sequester fossil carbon added to the active carbon cycle of the biosphere as carbon dioxide (CO_2) through burning of fossil fuel. Arable land refers to the most productive land that is being cultivated *e.g.* for food, animal feed, and biofuel crops. Pasture refers to unimproved grazing land, most often used for cattle farming. Forest refers to both natural forests and tree plantations. Built-up land refers to areas used for human settlements, roads and water power. Productive sea refers to that part of the 36 billion ha of ocean area on the planet that provides the bulk of marine production. It encompasses roughly 8% of the ocean area, concentrated along the world's continental coasts, and provides over 95% of the production of the sea catch. Adding these six major component areas results in the ecological footprint (Wackernagel, Lewan & Borgström Hansson, 1999).

As humans use goods and services from all over the world and affect faraway places with their waste and environmental impact, ecological footprints sum these biologically productive areas wherever they are on the globe into one aggregated footprint area. Wackernagel and Rees (1996) also multiply the areas by equivalence factors, different factors for each one of the six types of bioproductive areas. The equivalence factors are also different for each country, since biological productivity varies between different parts of the globe. These factors provide information about the category's relative yield (measured in primary or green biomass productivity) as compared to world-average space, which is given the equivalence factor of 1. By expressing footprints and biocapacity in average areas with world-average yield, they become internationally comparable, and different nations can, according to the authors, be compared with each other.

Other footprinting and area-based studies have been conducted in addition to the EF. Some calculate the actual productive area needed, without the use of equivalence factors, for example studies of land requirements relating to food consumption patterns in the Netherlands (Gerbens-Leenes & Nonhebel, 2002; Gerbens-Leenes, Nonhebel & Ivens, 2002), a study of land area for food consumed in the United Kingdom (Cowell & Parkinson, 2003) and calculations for appropriated (ecosystem) areas for Swedish food consumption (Deutsch, 2004).

EF is a pedagogic tool that makes the environmental impact of human actions easy to visualise. Areas are often easier to visualise than volumes, amounts of energy or monetary values, but the area calculated is also very anonymous. It is not specified where the area is placed, and taking action to make changes can seem difficult for the individual.

High input of external resources often result in increased yields, lowering the direct area needed to produce the same amount of crops compared to a system where less inputs of external resources are used. However, the indirect area needed to back up the external inputs, such as ecosystem areas for sequestering carbon dioxide from burning fossil fuels in traction and manufacture of fertilizers and agro-chemicals, do not show up if only direct area is considered (Deutsch, 2004). EF researchers are working on including more biologically productive areas in their studies. However, not all activities can be translated into biologically productive areas.

The calculation of area for biodiversity is very arbitrary in a EF study. According to Wagernagel & Rees (1996) and the EF-methodology, an additional 12% of land use needs to be set aside for biodiversity. There is no scientific base that 12% is enough. Their figure in turn comes from The Brundtland Commission's report on our common future, which states that 4% of the earth's land area is managed explicitly to conserve species and ecosystems, and the same report also states that 'a consensus of professional opinion suggests that the total expanse of protected areas needs to be at least tripled if it is to constitute a representative sample of earth's ecosystems' (The World Commission on Environment and Development, 1987).

The fossil energy land corresponds to the area needed for newly planted forest to sequester fossil carbon added to the atmosphere. In order for this to have a positive impact on the green house effect these forests then need to be left un-touched, or the CO_2 will be released into the biosphere again.

Emergy synthesis

Ultimately, the energy that is driving all processes on the globe comes from the sun, the Earths deep heat and from tidal energy. Many natural processes and ecosystem services in the biosphere, such as wind and rain, are products of those three driving forces. For example, the solar energy is converted into useful energy by plants. Animals and humans get energy from eating the plants and animals. We use energies of various qualities such as fossil fuels, bio-fuels and wind, which have all originally been generated from solar energy, the Earths deep heat and the tidal energies.

Emergy is the amount of energy required to make something, *i.e.* it is the 'memory of energy' (Scienceman, 1987) that degraded in transformation processes according to the thermodynamic laws. The more work done to produce something, the more energy transformed, and the higher the emergy value of that which is produced. It is a measure of the environmental work, both in past and present, necessary to provide a given resource. It is a measure of the global processes required to produce something expressed in units of the same energy form, most often solar energy. The method is based on the science of systems ecology (Odum, 1994), grounded in thermodynamics and general systems theory. Since all driving processes (the sun, earth's deep heat and tidal energy) supporting the biosphere is incorporated in the scientific background, an emergy evaluation includes all processes and resources involved in supporting a system.

Resource use is calculated into solar energy required to make something by the use of *transformaties*, specific for each transformation. The transformity is the ratio of emergy required to make a product to the energy of the product. Solar emergy is expressed in solar emergy joules (solar emjoules, sej), while solar transformity is expressed in solar emergy joules per Joule of output flow (sej/J).

It is a "top-down" approach, *i.e.* rather than dissect and break apart systems and build understanding from the pieces upward, emergy analysis strives for understanding by grasping the wholeness of systems. Evaluation starts with systems diagramming to obtain an overview of the system, its parts and processes, the problems, the contributing factors, and alternatives for management, *etc*. The pathways in the overview diagram represent flows of goods and resources. The emergy in each flow is calculated by the use of transformaties specific for each flow, and they determine the line items in an emergy evaluation table where all calculations are presented. (For example, see chapter *Emergy synthesis and emergy footprint of food consumption in Sweden 1996 or* Appendix A.) Because emergy measures what comes into a systems window, it is a property of the larger network surrounding it, and therefore it cannot be evaluated without some knowledge of the larger environment. Often it is desirable to use two systems windows to evaluate something, one for the local evaluation and a larger one to understand how the smaller window is being affected by the surroundings. (Odum, 1996)

All resources that are needed to produce something are accounted for, and aggregated into renewable resources (R), non-renewable resources (N), purchased goods (G) and services (S). The renewable and non-renewable resources are drawn from the environment and are free in the sense that we do not pay for them. The goods and services are invested resources from the society, and they are also regarded as feedback (F) from the society to the system that supports it with a yield (Y). A fuller explanation of concepts, principles and applications on emergy can be found in "Environmental Accounting" by H.T. Odum (1996)

According to Björklund (2000), the strength of emergy synthesis is that it is an eco-centric approach instead of anthropocentric. It also attempts to consider quality differences in resources and services, and it can be used in both ecological and economic systems. Weaknesses of emergy synthesis are, according to the same author, the methods difficulty in dealing with multiple yields from the same system, and dealing with ecosystem services and biodiversity. However, emergy synthesis can more easily measure ecosystem services and biodiversity aggregated, giving a measure of the whole system's requirements of support (J. Björklund, pers.comm.).

The presentation of results from an emergy synthesis also often lacks the pedagogic simplicity of, for example, the ecological footprint. Some scientific knowledge is required of the viewer in order to understand the results from an emergy synthesis. However, once understood, an emergy systems diagram can visualise a lot of information about a system in just one diagram.

Agricultural area for food consumption in Sweden 1997-2000 – A study of the direct and semi-direct areas

Introduction

Most of today's food production (>90%) uses agricultural land area. The area needed to feed a population depends on the yields per hectare on the one hand, while on the other it depends on the consumption pattern of the population, *i.e.* how much of certain foods are consumed. Agricultural area is a resource that is under the threat of increasing degradation. With escalating trade we are also responsible for impact on agricultural land in other parts of the globe. Because of concern for future food security, agricultural land resources are naturally the focus of much research. How are we using this land today, and how could we act more sustainably?

Direct land areas

Arable land (crop land) and *pasture land* (grazing land) together make up the available *agricultural land*. This agricultural land directly used for agricultural production is from here on referred to as *direct land area*. In the period 1997-2000, Sweden had on average an agricultural area of 3.2 million ha in production, with 2.8 million ha being arable land and more than 0.4 million ha permanent pasture land (Statistics Sweden, 2004a). Figure 4 shows how the agricultural area was used in Sweden for the same time period.

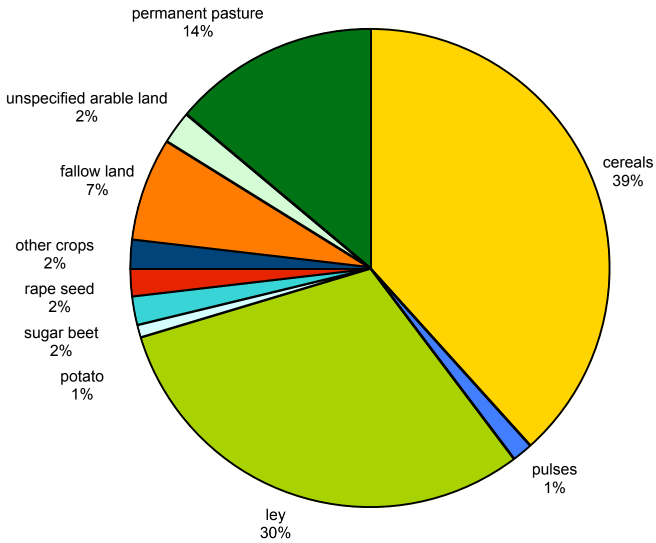

Figure 4. Agricultural use of Sweden's 3.2 million ha of agricultural land in 1997-2000 (Statistics Sweden, 2004a).

Crop production in Sweden was 1997-2000 strongly dominated by cereals and ley. The cereals grown on the largest areas was wheat and barley followed by oat, triticale and rye. Barley is most often used as feed for cattle and pigs, and wheat is used for both human and animal consumption in Sweden. Ley is most commonly various grass and clover crops, mostly intercropped, for production of roughage (e.g. hay and silage) and grazing, often kept 2-3 years in a row in the crop sequence on the same field. Therefore, in addition to pasture land, it is common in Sweden for dairy and cattle farmers to also use arable land for grazing. Ley is sometimes sown for grazing alone, or farmers let their cattle graze during the second half of the growing season after one or two harvests of roughage. The proportion of leys increases towards the north and makes up most of the area of arable land in the northern part of Sweden. Oilseed crops, mostly rape seed, are mainly located on the plains of southern Sweden, as is production of sugar beet. Potatoes are grown throughout the country. The average crop yield varies in different parts of Sweden, and can vary by as much as a factor of 1 to 3.5 between the more productive south and the colder north (Statistics Sweden, 2001).

Note that in this study agricultural area appropriated in Sweden as well as abroad is defined as *direct area*, since this area is *directly* used for agricultural production. Direct area outside a nation's borders has in past studies sometimes been referred to as indirect area, or *ghost* area (Borgström, 1973), since it is out of sight. Crops, unprocessed or processed, fed to animals are called *fodder* in this study. Fodder is most commonly *roughage*, *i.e.* hay or silage, *grain* (cereals, in Sweden most commonly barley, oats and triticale) and *manufactured feed*. Manufactured feed (in some studies called *concentrate*) is processed and high in energy and protein ingredients such as cereals, pulses (peas) and oil-bearing crops (*e.g.* soya beans and rape seeds and most often by-products thereof).

Semi-direct land areas

In order for the food production system to work, more agricultural area than the actual agricultural land where the food is produced is needed. Fallow land is important land for the agricultural system, even if it does not produce food during the fallow years. Fallow land consists of two kinds in particular; agricultural (beneficial for the cropping system) and political (beneficial for the economic system). This agricultural land that is not directly used for agricultural production is titled *semi-direct area* in this thesis.

Fallow land for agricultural reasons is part of the crop sequence and used for weed control and is beneficial for the crops that grow in the following year, thus increasing the next year's yield. Agricultural fallow may be bare land bearing no crops at all, land with spontaneous natural growth which may be used for feed or ploughed in, or land sown for green manure. Green manure crops are often crops grown for their nitrogen fixation abilities. They grow for a season, concentrating nitrogen in their biomass and once ploughed in, the nitrogen is released for the benefit of the next years' crops. This decreases the overall use of external nitrogen fertilisers.

Our food production system is regulated by political and economic systems. Farmers are subsidised to set aside arable land from production for macro-economic reasons, *e.g.* subsidised fallow land to reduce over-production of certain crops and increase prices. This fallow land is beneficial for the country's economy since it helps keep prices up on crops produced. It is deemed cheaper for a country to pay its farmers subsidies than to take the cut-back of low prices. Political or not, this fallow land has a biologically beneficial effect on the following years' crops as well.

The fallow land can be taken into production at fairly short notice if necessary, although one must then remember that the average yields on all production in the crop rotation system may decrease, since the fallow land helps increase yields in other years. If the fallow land is taken into production, the total yield from all arable land may not increase much, or even not at all. Instead, the use of external non-renewable inputs may increase to compensate for the benefits that the fallow land contributed to the system.

This semi-direct area is seldom accounted for in area-based studies, especially in studies with a bottom-up approach where area is calculated by how much food is consumed per capita in weight and then multiplied by a yield to get an area (Gerbens-Leenes & Nonhebel, 2002). However, the semi-direct areas are relevant for the functioning of the contemporary food system as a whole, and are therefore included in the *foodprint*. If these areas were not set aside, over-production could change the global market and world prices, thus also changing our economy, consumption, food system and *foodprint*.

Earlier studies of agricultural area for food production

Earlier area-based studies of food consumption on a national scale include *e.g.* Gerbens-Leenes *et al*. (2002), who calculated the land requirements for food in the Netherlands for 1990. They restricted their statistics to foodstuffs consumed in the household, thus leaving out a major proportion of food consumed at schools, restaurants and workplaces. Cowell & Parkinson (2003) localised the land area for food consumed in the UK for 1992. An earlier study of appropriated area for food production conducted for Sweden by Deutsch (2004) for 1962 and 1994 showed how the size of appropriated agricultural area had changed between these two years. Their study included water area for fish production, but excluded some other areas such as beverages. In all the above studies, statistics for only one year were used. None of the above included fallow land.

Objective

The objective of this study was to calculate the entire agricultural area supporting food consumption in contemporary Sweden, both the direct and the semi-direct areas.

Materials and methods

I used the foodshed approach as suggested by Getz (1991), monitoring Swedish borders over which food passes and documenting it. To determine direct land use for food consumption in Sweden, I used statistical data on domestic land use (Statistics Sweden, 2002), statistics on imports and exports (Statistics Sweden, 2002), yield statistics (FAOSTAT, 2003; Statistics Sweden, 2004b) and conversion factors (USDA, 1992; FAO, 2001). To determine the semi-direct land area I used statistical data on fallow land (Eurostat, 2000; Statistics Sweden, 2001).

Data collection

The amount of data collected for this study was extensive. Most data were collected on-line from statistical databases, and then processed in EXCEL™ spreadsheets, some with the help of macro programmes.

The trade statistics kept in the Swedish Statistics (SCB) database are collected by Tullverket (Swedish Customs and Excise), and there is no record of *country of origin* for imported food since 1995, only the last *country of port*. Therefore foodstuffs are hard to trace back to the country in which they were produced. This applies especially to foodstuffs such as tropical fruits, stimulant crops and soya products, which arrive by ship at large ports in the EU and then are sent on to Sweden. Therefore statistics on origin of imported food should be interpreted with care.

Data calculations

The direct area (DA) for producing food consumed in Sweden for the period 1997-2000 was calculated using the following equation:

$$DA = D + I - E$$

where D is the domestic area (ha), I is the imported area (ha) and E is the exported area (ha). Data for D were collected on an area basis (Statistics Sweden, 2000). An area (A) for every foodstuff imported and exported was calculated using the equation:

$$A = C*cf/Y$$

where C is the amount of foodstuff (t), cf is a conversion factor (%) for converting a foodstuff back to the original crops and Y is the crop yield (t/ha) in the specific country where these were produced. These areas (A) were then added together into total I and total E respectively.

The equation D + I – E do not exactly add up to DA on a yearly basis. Some foods, especially grains, are stored in stocks and are not consumed, or exported, within the year of production. According to the same logic, some foods consumed are not imported or domestically produced in the same year they are produced. However, the use of data from 4 years was assumed to even this out.

The foodstuffs consumed in Sweden were divided into the categories presented in Table 4. To a large extent these categories follow the categories FAO use to classify food commodities in their database FAOSTAT (2003). Cowell & Parkinson (2003) used a similar categorisation in their study of the UK. However, there were some differences in the present study. I aggregated animal products (*meat* and *other animal products*) and fodder crops to fodder crops alone, since animal products were converted to area for growing fodder crops. *Tobacco and derived products* were excluded from this study since they are not regarded as food. NES (not elsewhere specified) was a new category including foods with mixed ingredients from several categories, or food of unknown origin. Fish, and other food of marine origin, was also excluded. Note that the bold text in the category definitions in Table 4, indicates the terms used hereafter in the text.

Table 4. Food categories used in this study of Swedish food consumption, and examples of common foodstuffs in each category. The categories mainly follow the categories of FAO statistics (FAOSTAT, 2003). Bold text indicates category term used from here on in the study

Food category	Common foodstuffs
Cereals and cereal products	Bread grains, flour, pasta and bread
Roots, tubers and derived products	Potatoes,
Sugar crops and sweeteners and derived products	Refined sugar
Pulses and derived products	Beans, peas
Nuts and derived products	Fresh and roasted nuts
Oil-bearing crops and derived products	Cooking oil, margarine
Vegetables and derived products	Fresh and prepared vegetables (sweet corn)
Fruits and derived products	Fresh and prepared fruits and berries (orange juice)
Spices	Spices and herbs
Fodder crops and animal products	Green fodder, grains and manufactured feed, meats, dairy and eggs
Stimulant crops and derived products	Coffee, tea and cocoa products
Beverages	Wine, beer and spirits
NES[a] foodstuffs	Foods with mixed ingredients from above, or food of unknown origin

[a]NES = not elsewhere specified

The domestic area (D) in this study was the agricultural area in Sweden used for producing food alone, either for direct consumption or for feed used to produce animal products, such as meat and dairy. I excluded the agricultural area used for bio-fuel production, such as willow and wheat for ethanol production for energy. Area for keeping horses was also excluded. Data for D were collected on an area basis and no conversion factors were needed (Statistics Sweden, 2000). D was then allocated to the categories shown in Table 4. Some statistics had to be investigated further and separated in order to place them in the correct categories. For example, wheat can be processed into bread, fodder and beverages (alcohol) and therefore had to be correctly divided among the three categories.

Imported and exported foodstuffs are categorized following an established nomenclature known as the combined nomenclature (CN), based on the International Convention on the Harmonized Commodity Description and Coding System (known as the Harmonized System, HS) (Tullverket, 2004). The traded foodstuffs in this study are included in chapters 02, 04, 07-12, 15-23 as shown in Table 5. More detailed explanatory notes to the CN codes can be found at

Tullverket (2004). Note that not all foodstuffs in each chapter were included in this study, *e.g.* oils for technical use were excluded in the area calculations.

Table 5. Combined nomenclature (CN) chapters included in this study

CN chapter	Chapter includes
02	Meat and edible meat offal
04	Dairy produce; birds' eggs; natural honey; edible products of animal origin, not elsewhere specified or included
07	Edible vegetables and certain roots and tubers
08	Edible fruit and nuts; peel of citrus fruits or melons
09	Coffee, tea, maté and spices
10	Cereals
11	Products of the milling industry; malt, starches; inulin; wheat gluten
12	Oilseeds and oleaginous fruits; miscellaneous grains, seeds and fruits; industrial or medicinal plants; straw and fodder
15	Animal or vegetable fats and oils and their cleavage products; prepared edible fats; animal or vegetable waxes
16	Preparations of meat, of fish or of crustaceans, molluscs or other aquatic invertebrates
17	Sugars and sugar confectionery
18	Cocoa and cocoa preparations
19	Preparations of cereals, flour, starch or milk; pastrycook products
20	Preparations of vegetables, fruit, nuts or other parts of plants
21	Miscellaneous edible preparations
22	Beverages, spirits and vinegar
23	Residues and waste from the food industries; prepared animal fodder

(Tullverket, 2004)

Conversion factors (cf) were used for converting imported and exported food stuffs back to the original crops, for example to calculate how many tons of oranges were used to produce a ton of orange juice. Animal products, such as meat, dairy and eggs, were calculated back to the fodder used to keep the animals. Most conversion factors were world averages obtained from FAO (2001) or USDA (1992). I calculated some new conversion factors for this study when relevant values were not found in the literature.

Results

Direct land areas

The net direct agricultural area (DA) for food consumption in Sweden for the period 1997-2000 was found to be a little more than 3.7 million ha on average, see Table 6. This corresponds to 0.41 ha per capita. The domestic area producing food was 2.7 million ha, whereof fodder area was the major area use. The imported area was 1.9 million ha, also dominated by fodder area. The exported area, which to some extent is imported area, *e.g.* area for coffee and oil-bearing crops that are re-exported, was 0.8 million ha, *i.e.* a little less than half the imported area in size. With agricultural trade at this general level, it is hard to assess exactly how much of the food exports originate from crops produced domestically or from imported ingredients. To calculate this more exactly, further investigation of the food industry would be necessary and this was not done in this study.

Table 6. Direct agricultural areas (ha) appropriated for food consumption in Sweden 1997-2000

Category	Domestic area (D)	Imported area (I)	Exported area (E)	Net consumption area (DA)
Cereals	294 352	110 916	106 791	298 477
Roots and tubers	36 624	8 099	665	44 058
Sugar crops	58 640	12 263	14 052	56 851
Pulses	5 892	3 774	2 280	7 385
Nuts	0	20 373	499	19 874
Oil-bearing crops	77 908	230 967	94 366	214 509
Vegetables	16 399	21 465	6 730	31 134
Fruits	20 935	65 616	4 356	82 195
Spices	226	7431	387	7 269
Fodder crops	2 136 937	1 079 842	447 488	2 769 291
Stimulant crops	0	261 591	70 590	191 002
Beverages	21 376	35 905	46 031	11 249
NES	5 700	213	0	5 913
Total	2 674 988	1 858 452	794 235	3 739 206

[a]NES = not elsewhere specified

The most dominant food area was that of fodder crops for animal production, see Figure 5, corresponding to 74% of Swedish net consumption area. Fodder area was mainly area for producing roughage (hay and silage), grains (cereals) for direct feeding, or as part of manufactured feed. Manufactured feed also contains by-products rich in proteins, such as cakes from rape seed and soya beans from oil production. Fodder area was followed far behind by cereals (*e.g.* wheat, rice and maize) for human consumption with 8% of the net consumption area. Note that cereals fed to animals were categorised as fodder crops in this study. Next came area for oil-bearing crops with 6% and stimulant crops with 5%. The remaining categories fruits, sugar crops, vegetables, roots and tubers, nuts, beverages, spices, pulses and NES together made up the remaining 7% of area.

Direct areas for potatoes, garden vegetables, fruits and berries that are home grown were estimated using statistics on how much of these foods are produced at home and calculating them into an area. In the 1999 survey, own-produced foods such as potatoes, fruit and berry preserves, *etc*. consumed in Sweden were calculated to represent about 19 000 ha. In addition, 19 000 tons of meat consumed in Sweden was from reindeer, which graze freely in the forest and on the mountain areas of Northern Sweden, and hunted wild animals, such as moose and roedeer, in the year 2000 (Statistics Sweden, 2004b). However, this was not translated into an area.

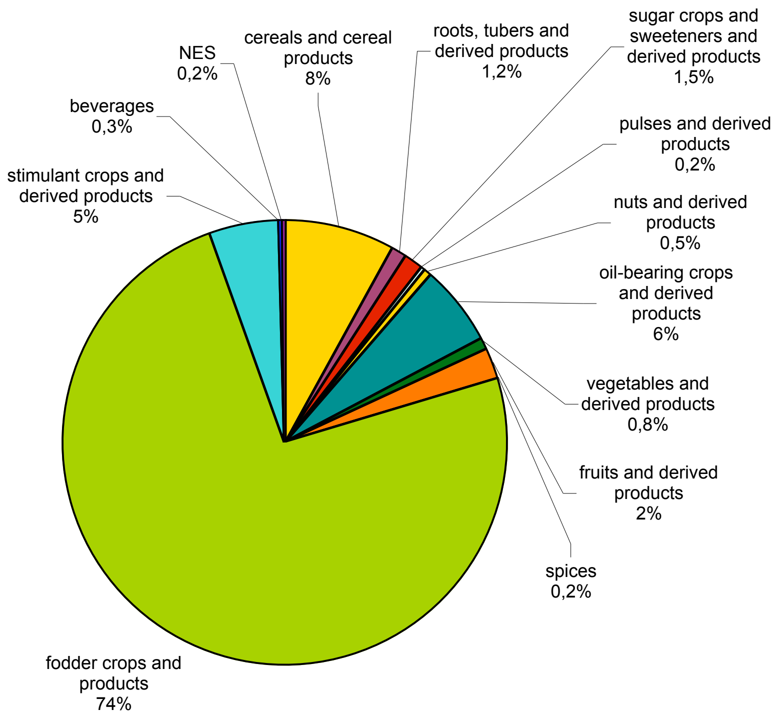

Figure 5. Direct agricultural area (DA) for food consumed in Sweden 1997-2000. (Note that cereals fed to animals were categorised as fodder crops).

Domestic agricultural land use is shown in Table 7, including all agricultural land in production in Sweden 1997-2000, even area that produced food for export. The *crop* column shows the crops grown in Sweden and the *category* column shows the food category to which these crops were allocated. The main crop areas were for ley, pasture (both sown ley and permanent pasture) and cereals for fodder, *i.e.* crops that all fall under the fodder crop category. Total agricultural land for food production in Sweden was on average 2.67 million ha 1997-2000, with a decrease from 2.75 million ha in 1997 to 2.56 million ha in the year 2000. This corresponds to a decrease of 7% in the period of study.

Table 7. Domestic direct land area (ha) for food consumption in Sweden for each year 1997-2000 and average of the four years. Food is categorised as described in Table 4 and in the crop column the original crop is listed. Data are from Swedish Statistics (Statistics Sweden, 2000), although the data were modified according to the notes

Crop	Category	1997	1998	1999	2000	Average
Wheat	Cereals[a]	206 369	232 894	178 983	239093	214 335
Wheat (for fodder)	Fodder crops	95 870	114 888	67 085	113024	97 717
Wheat (for vodka)	Beverages	20 972	25 132	14 675	24724	21 376
Rye	Cereals	29 416	34 617	24 507	34553	30 773
Barley	Fodder crops	482 900	444 960	481 987	411224	455 268
Oats	Fodder crops[b]	190 192	186 394	180 875	171267	182 182
Oats	Cereals[c]	15 773	15 573	15 283	14777	15 352
Triticale	Fodder crops	66 473	66 751	32 586	40728	51 635
Grain, mixed	Cereals	30 247	26 972	33 022	45328	33 892
Peas	Fodder crops	27 742	44 150	25 053	22892	29 959
Peas	Pulses[d]	5 000	5 000	5 000	5000	5 000
Peas	Vegetables	9 028	8 524	8 752	8525	8 707
Beans	Pulses	921	938	872	835	892
Ley	Fodder crops[b]	914 128	893 330	882 599	797848	871 976
Potato	Roots and tubers[e]	38 630	36 517	35 630	35720	36 624
Sugarbeet	Sugar crops	60 459	58 737	59 881	55484	58 640
Rapeseed	Oil-bearing crops	63 582	54 572	75 889	48168	60 553
Linseed	Oil-bearing crops	9 534	15 056	34 172	10660	17 356
Vegetables	Vegetables[e]	8 507	7 774	8 008	6476	7 691
Fruits	Fruits[e]	9 894	9 635	9 718	9178	9 606
Berries	Fruits[e]	11 802	11 377	11 512	10623	11 329
Herbs and spices	Spices	256	229	237	182	226
Other crops	NES	3 978	2 999	5 376	10447	5 700
Permanent pasture	Fodder crops	449 651	448 855	447 149	447149	448 201
TOTAL		2 751 323	2 745 873	2 638 852	2563905	2 674 988

[a] ethanol for energy subtracted
[b] horse feed subtracted
[c] approx. 5% of oats are rolled oats for human consumption (B. Mannerstedt-Fogelfors, pers.comm.)
[d] 5 000 ha per year are dried peas for pea soup (Sw. *ärtsoppa*) (L. Ohlander, pers.comm.)
[e] Vegetables, fruits and berries include home garden areas which amount to more than 19 000 ha

Sweden re-exports many food stuffs, *e.g.* bananas, and coffee. Some of these re-exported foodstuffs are processed into new foods, such as green coffee into roasted coffee, cereals into baked goods, *etc*. Therefore some of the exported area ought to be subtracted from the domestic area and some from the imported. However, it is hard to tell exactly where the exported area originates, which means that it is not possible to exactly know how much of the net consumed area is imported. The last country of port is shown in Table 8. This is not to be confused with country of origin.

Table 8. The last country of port for each food category (ha per year 1997-2000)

Category	Africa	South America	Oceania	Europe	Asia	Central America	North America
Cereals	47	75	540	88 301	8 917	0	13 037
Roots and tubers	2	0	0	7 880	26	0	191
Sugar crops	1	0	0	12 219	22	8	12
Pulses	5	84	217	1 491	685	26	1 266
Nuts	48	8	27	10 277	6 607	0	3 405
Oil-bearing crops	2 188	459	298	215 438	8 414	1 344	2 825
Vegetables	62	180	153	15 878	2 244	161	2 786
Fruits	1 425	1 811	221	53 998	3 396	2 559	2 206
Spices	51	4	0	4 159	2 120	748	349
Fodder crops	4 232	27 907	2 859	1 002 238	41 456	0	1 151
Stimulant crops	14 255	73 196	305	157 312	3 167	13 160	196
Beverages	602	970	685	31 517	295	81	1 755
NES	0	0	0	108	101	0	4
Total	22 917	104 693	5 305	1 600 816	77 452	18 087	29 182

Semi-direct land areas

In this study, fallow land was calculated using the equations:

Semi-direct land (Sweden) = DA*7% (Statistics Sweden, 2001)

Semi-direct land (imported) = DA*5% (Eurostat, 2000)

In 1997-2000, fallow land area in Sweden was on average 7% of total arable land (Statistics Sweden, 2001), compared to 5% in the EU in 1997 (Eurostat, 2000). This varies in the 15 EU countries, ranging from less than 1% in Greece to more than 15% in the Netherlands. The total area of fallow land in the EU for the same year was 5.5 million hectares of arable land, of which 3.0 million ha was agricultural fallow and 2.5 political. The fallow land in the EU corresponds to more than the total agricultural area in Sweden.

Total agricultural areas

The total agricultural area for food consumed in Sweden 1997-2000, direct and semi-direct area together, was approximately 4 million ha, see Table 9.

Table 9. Total agricultural area (ha) for food consumed in Sweden 1997-2000

	Total area	Area per capita
Direct land area	3 739 206	0.42
Semi-direct land area	261 744	0.03
Total agricultural area*	4 000 950	0.44

*Rounding up areas per capita results in sum of total not adding up exactly.

Caveats

I attempted to exclude agricultural area used for producing crops for non-food use. However, some of these areas may have been accounted for in the calculated area due to limited information. One such area is vegetable oil, which in the statistics has not been categorized as for technical use only, *e.g.* linseed oil used for wood protection and paint, and was thus included here. The same goes for crops used for medicinal purposes, such as oils from herbs, but these areas are most probably very small in this context.

Some imported foodstuffs are processed with several different ingredients from two or more categories. For instance, some cereal and dairy products include various amounts of sugar, which were not included in the sugar crop category since the exact amounts were unknown. In this study these foodstuffs were categorised with the major, dominating ingredient. For instance, all pastas were allocated to the cereal category, even though some may contain eggs. Most baked goods were allocated as products of wheat, even though they most certainly contain many other ingredients such as fats, sugar, eggs, *etc*. They may even include other grains as well as wheat, but when nothing was specified in the statistics these were calculated as wheat. Cereal ingredients were sometimes assumed to be wheat, as in baked goods and unspecified alcoholic drinks, even though they may be something else. Whenever a cereal ingredient was unknown it was calculated as being wheat. Glucose, dextrose, fructose, and other sugar syrups of unknown origin were calculated as corn syrup derived from maize. Imported sugar, when not specified, was assumed to originate from sugar cane, rather than sugar beet, since sugar cane is the most commonly grown sugar crop in the world.

Data presented by international organisations like the FAO are often based on estimations, but they are used by researchers because they are the best available (Buringh, 1989). For most crops a specific yield was used for the specific country of origin when origin was known. World average yields were used as sparingly as possible, mainly where the imported or exported quantities were small, to simplify data collection. World average yields are often low since they are an average of all countries that grow a certain crop. For example, many countries grow bananas, but the average yield in each country varies greatly. The world average banana yield in 2000 was 16 t/ha, while Costa Rica had a yield of 54 t/ha and Panama 62 t/ha for the same year. Both countries are large export countries. In the latter case the arable area would be overestimated by a factor of almost 4 if the world average was used. The countries exporting bananas often have intensified production systems and yields are generally substantially larger than world average yields. This is true of other products too. When the country of origin was unknown, for instance with bananas re-imported by Sweden from the Netherlands or Germany, an average of the largest banana producers was used instead of the FAO world average.

Because the statistics for some foodstuffs are aggregated, fresh, frozen and/or dried food may be kept together under the same CN code, and they cannot be separated into specific preparations. This means that an appropriate conversion factor was not found and used. Food that I allocated as unprocessed may in fact be dried or frozen for conservation, but not otherwise prepared. Fresh fruit may be frozen or dried, but not otherwise prepared and was calculated as being fresh. However, the amounts of these foods are on the whole very small and falsely calculating them as fresh makes no significant difference in this study.

There is some double counting, *e.g.* area for soya oil and fodder cakes from soya bean were both included in the study even though they are co-products from the same crop. However, the areas for oil-bearing crops are smaller that the areas for fodder cakes for *e.g.* soya, and the area double counted is relatively small. It is my assumption that the areas double counted are compensated in the total DA by the areas not accounted for due to problems mentioned above.

Discussion on agricultural areas used and effects of dietary changes

First, one must note that Sweden is very fortunate in that it has more arable land area per capita, 0.31 ha, than the average global citizen, 0.23 ha per capita. And we could, if need be, most probably take even more into use. The agricultural area in Sweden reached its maximum in the 1920s when it had 5.0 million ha of agricultural area (Statistics Sweden, 1930), to compare with 3.2 million today. The area that has gradually been taken out of production, due to increased productivity but also due to more direct subsidies *e.g.* to plant forest to decrease or avoid problems with overproduction, could probably with some effort be taken back into production in future if needed. It is also noteworthy that the relationship between fertile arable land to land mostly suited for grazing is much higher than that for the world average citizen. Even so, Swedish consumption of food, what Swedes choose to eat, leads to a deficit in its direct land use. Sweden has a larger direct consumption area, 3.7 million ha, than it currently has agricultural area within its borders, 3.2 million ha, meaning that Swedes not only have more area per capita than the average world citizen, but that they use even more than this. In addition, most Swedish citizens are probably unaware of how this area outside the national borders is used, or how the people that work the land are feeling and how they are doing. From a sustainability and fairness perspective, one might think that Sweden should be a net exporter of food instead of a net importer, especially as the country has favourable freshwater resources and a climate with cold winters that allows it to produce food with less chemical pesticide use. However, climate is not totally in our favour when it comes to attaining high yields due to its cool climate.

Could Sweden be self sufficient in its food production? Sweden is not self-sufficient when it comes to agricultural food production, see Table 10. It relies on agricultural area abroad for about one third of its food. Some of the foods imported to Sweden are not suitable for growing in the Swedish climate, such as coffee, cocoa, some nuts and of course tropical fruits. From an area point of view, these are not large areas compared to the area used for fodder crops. However, most of the agricultural area is within Swedish borders.

Table 10. Direct agricultural area for food consumption (m^2 per capita) in Sweden 1997-2000

Category	Net consumption area per capita	Domestic area per capita	Self sufficiency, %
Cereals	332	327	99%
Roots and tubers	49	41	83%
Sugar crops	63	65	103%
Pulses	8	7	80%
Nuts	22	0	0%
Oil-bearing crops	238	87	36%
Vegetables	35	18	53%
Fruits	91	23	25%
Spices	8	0	3%
Fodder crops	3 077	2 374	77%
Stimulant crops	212	0	0%
Beverages	12	24	190%
NES	7	6	96%
Total	4 155	2 972	72%

Complete self-sufficiency may not be desirable for various health reasons. For instance, Swedish soils are low in selenium, which leads to low selenium contents in Swedish crops and a deficiency in the Swedish population (Statens livsmedelsverk, 1994), making import of more selenium-rich foods beneficial. However, in Finland selenium is added to fertilisers, which is another option. (J. Helenius, pers.comm.) Current dietary guidelines advise Swedes to eat more fruits, vegetables and polyunsaturated fats from nuts and avocados, foods that often grow in warmer climates. Swedes are also recommended to eat more colourful foods, and yellow, sweet mangoes and purple aubergines may seem much more appealing than the relatively pale domestic apples and parsnips. Sweden could be more self-sufficient in some foods if it wished, by its residents either changing their choice of crops for some foods, *e.g.* rapeseed for vegetable oil instead of palm oil or eating less of some foods, *e.g.* meat and other animal products and instead eating more pulses. In time, Sweden would probably also become better at producing and harvesting colourful berries and varieties of roots and tubers. The market needs time and space to adjust to new, domestic production and distribution systems.

Although improved agricultural practices are important in limiting the environmental impact of the food sector, the potential contribution of changes in dietary choices should not be neglected (Reijnders and Soret, 2003). Throughout the world there appears to be a direct link between dietary preferences, agricultural production and environmental degradation (Goodland, 1997; Carlsson-Kanyama, Ekström & Shanahan, 2003). 'First-step-food' is an operational proposal for environmentally sustainable dietary guidelines for Sweden. According to its inventors, it is a constructive suggestion for a healthier and more environmentally friendly diet (Lindeskog & Dahlin, 1999). The diet has been developed for Sweden by nutritionists in co-operation with a reference group of scientists with agendas in food, environmental and agricultural issues (Lindeskog & Dahlin, 1999). The recommendation is called 'First-step-food', since it is a proposal for *a first step* during a 10-year transition towards a diet more sustainable for our health and the environment. In the proposal, different aspects of nutrition, environmental issues and toxicology are considered. The 'First-step-food' diet will also probably reduce environmental impacts, such as emission of greenhouse gases, acidification and nitrogen emission to air and waters. Other positive effects, regarded and estimated in the diet proposal, are reductions in the use of agricultural chemicals, as well as maintenance and improvement of soil quality, biodiversity and the cultural landscape (Lindeskog & Dahlin, 1999).

Table 11. The dietary changes in 'First-step-food' compared to the contemporary diet in Sweden. + = increased intake, – = decreased intake. No percentage means a small shift in increase or decrease (Lindeskog & Dahlin, 1999)

Food	Change (%)	Food	Change (%)
Bread	+ 50%	**Fats/oils**	± 0
Cereals and grains	+ 50%	rapeseed oil	+
Potatoes	+ 40%	butter	– 100%
Pasta	± 0	light margarine	– 100%
Rice	–	margarine (bread spread)	++
Fruit and vegetables[1]	+ 60%	margarine (for cooking)	–
vegetables	+	**Meat**[2]	– 25%
roots and tubers	++	beef (grazing)	++
lettuces	–	beef (concentrate)	– 100%
fruits	+	beef (both)	–
juice	– 50%	lamb and sheep	+ 100%
Pulses	+ 10 times	pigs	– 50%
Milk,yoghurt buttermilk	–	poultry	– 50%
Cheeses	– –	**Eggs**	± 0
fat	+	**'non-nutrient-foods'** [3]	- 50%
light	– 50%		

[1]A shift towards more roots and tubers, and less greenhouse-grown vegetables. More Swedish and European fruits and less fruits from other parts of the world.

[2] No imported meat

[3] Food not necessary for nutrition, *e.g.* sugary drinks, wine, sweets, chocolate, cream, coffee, certain cheeses, ice-cream, cakes, *etc*.

Applying dietary changes in 'First-step-food' from Table 11, to the database of food consumed in Sweden 1997-2000, results in a decrease of the direct agricultural area used by more than 0.5 million ha, from 3.7 million ha to 3.2 million ha. Results are presented in Table 12 and Figure 6. The decrease brings agricultural area needed for food consumption in Sweden down to its domestic agricultural area in production today. This is equivalent to a 14% decrease. The large decrease in meat consumption did not bring down the total agricultural area use so much. This was both due to a large part of the meat consumed in the modified diet originating from grazing cattle and sheep, and also due to some other foods (pulses, cereals, potatoes, fruits and vegetables) increasing. There is a shift from greenhouse-grown vegetables towards more roots and tubers, which use more direct agricultural area. However, even though it has not been studies here in this thesis, it is reasonable to think that this would decrease the indirect areas needed for environmental support. For example, greenhouse-grown vegetables require more non-renewable resources and increase greenhouse gas emission than field-grown (Carlsson-Kanyama, 1998a). The *animal product* category includes different meats, dairy products and eggs.

Table 12. Total direct agricultural area (CA) for two different consumption patterns, the contemporary in Sweden 1997-2000 and one modified for better health and environment according to 'First-step-food' (Lindeskog & Dahlin, 1999)

Food	Contemporary agricultural area (ha)	Modified agricultural area (ha)
Cereals and grains (incl. rice & pasta)	298 477	447 716
Potatoes	44 058	61 681
Non-nutrient-foods	266 370	133 185
Pulses	7 385	73 854
Fats	234 382	234 382
Fruits and vegetables	113 328	181 325
Animal products	2 769 291	2 076 968
Total agricultural area	**3 733 293**	**3 209 112**

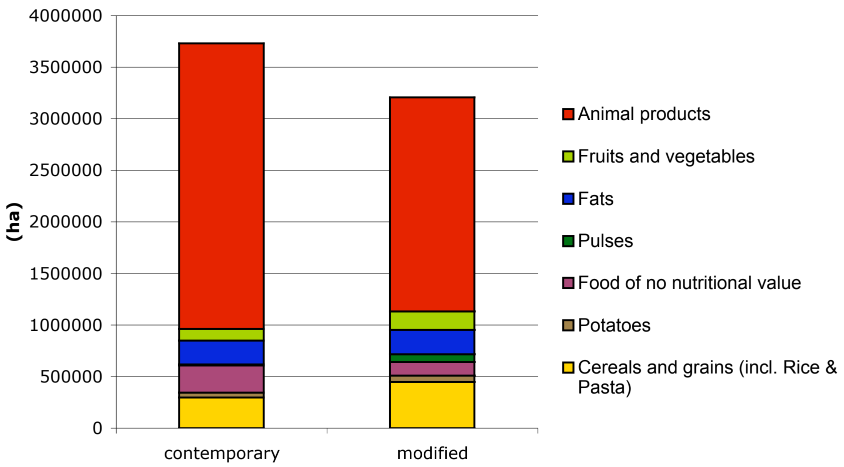

Figure 6. Comparison between agricultural area for a contemporary consumption pattern in Sweden (1997-2000) and a modified diet according to 'first-step-food'.

There area for animal products was the unquestionably the largest of all food categories in this study, 74% of direct agricultural land use. It is now also obvious that decreasing our meat consumption would also decrease the agricultural area use, as the example above shows. It rises the question; what is most important for reducing environmental load caused by our food consumption? What *we* eat, or what the animals eat? Discussing and designing *sustainable feeding plans* seems to be as important as *sustainable dietary guidelines* for humans. However, it would probably not be more sustainable to avoid eating meat all together. It depends on what kind of meat we choose to eat. One must remember that about two thirds of the global agricultural area is not used for, and may not be suitable for, cultivation, *i.e.* grazing animals are excellent at using land that is unavailable for cultivation and at converting plants that humans cannot eat into high value animal products. One must also remember that some of the biodiversity cherished in Sweden is dependent on its grazing animals. Animals are also excellent at converting by-products from the food industry into meat and dairy products. Moreover, leys are favourable to the cropping system and the manure that the animals produce can recycle plant nutrients and help maintain, and even increase, soil organic matter and thus fertility. Ley constitutes 30% of agricultural area in Sweden. Ley is only grown for the sake of animal production, but it is beneficial for the agricultural system. If there were no cattle, the ley would not be needed. If Sweden decreased consumption of meat from cattle and sheep, and thus had less ley in the agricultural system, this would release more area for other food production, but one must remember that less ley in the cropping system may mean smaller yields and/or larger use of non-renewable external inputs to make up for the ecosystem services provided by the ley. A large agricultural area for food products is not necessarily negative if it also contributes to positive side effects, such as sustaining biodiversity and reducing use of non-renewable resources.

Another issue when studying the world as a whole is that the richer populations in the North are likely to continue to eat meat, while they can pay for it, and will not restrict their meat consumption or consumption of exotic and long distance transported vegetables and fruits out of solidarity. Poorer populations in the South should be given the ecological space to increase their meat consumption in order to eat a healthier diet, since meat is considered to be an easy way to obtain protein of good quality for body growth. Meat also contains iron that is more readily taken up by the body than iron from vegetarian sources and it has an extra effect in that it increases iron uptake, the so-called 'meat effect'.

The fallow land appropriated for food consumption in Sweden is included in this study's semi-direct area. In addition, there has to be enough area within the system for producing stocks of food for years when crops fail and yields are decreased. Area for producing stocks is automatically included in the direct area. Fallow land could also be used for production with less resource use, which in general gives smaller harvests.

Figure 6 and Figure 7 compare the agricultural land area appropriated for food consumption in Sweden to a similar study for the Netherlands (Gerbens-Leenes, Nonhebel & Ivens, 2002). However, the two studies differ in several ways. The Netherlands study only considers food consumed in the household, neglecting a large amount of foods consumed at work and in restaurants. It also does not account for by-products that are used for livestock, although in the Swedish study these by-products of *e.g.* fodder cakes from soya bean oil production correspond to a larger direct agricultural area than the food oil extracted from the same soya bean. This is probably why the agricultural area for oil-bearing crops is so large in the Netherlands study compared to the results in this study. The agricultural area required for food consumption in the Netherlands is only 75% compared to the agricultural area for Sweden, see Table 13. This is probably due to the same reason as discussed above. The agricultural area required for food consumers in Sweden in 1994 was the same as the area in this study (Deutsch, 2004).

Table 13. Results on agricultural area required per capita for domestic food consumption from this present study compared to other studies

	Agricultural area appropriated per capita (ha)	Year of study
This study	0.44	1997-2000
(Gerbens-Leenes & Nonhebel, 2002)	0.35	1990
(Deutsch, 2004)	0.63	1962
(Deutsch, 2004)	0.44	1994

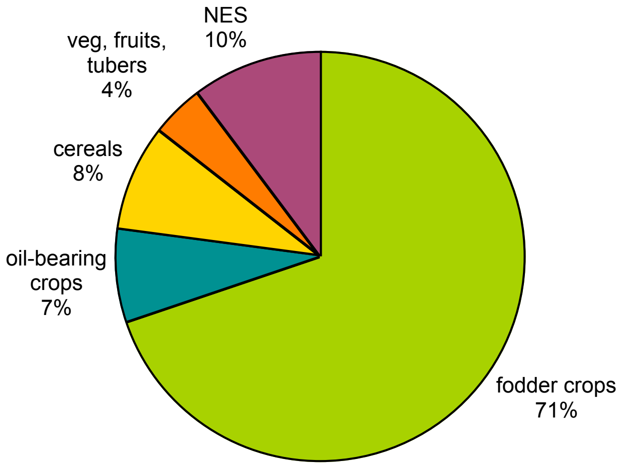

Figure 7. Agricultural land area for food consumption in Sweden 1997-2000. (Source: this study. However allocated to enable comparison with Netherlands study below.)

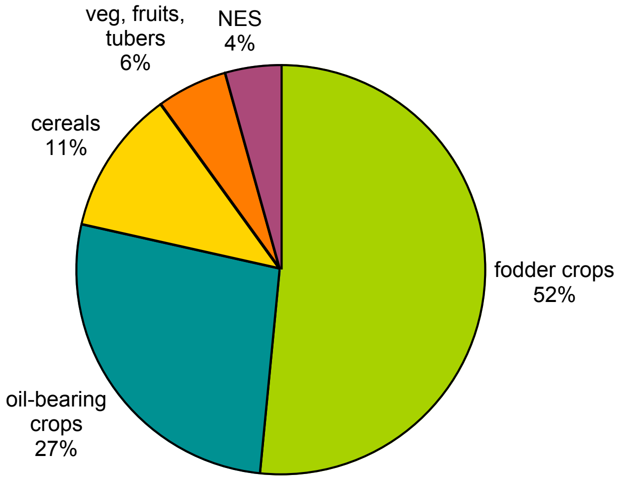

Figure 8. Agricultural land area for food consumption in Netherlands in the household (Gerbens-Leenes, Nonhebel & Ivens, 2002)

An effort to investigate the origins of bananas turned out to be unsuccessful. In Swedish trade statistics, a large fraction of the bananas were imported from Germany. Studies of the German trade statistics resulted in the finding that some bananas were imported from France, while further study of the French trade statistics revealed that bananas were imported from Germany (!). The consumer is informed of country of origin at the produce counter at the grocery store. However, the collected statistics on the national level lack transparency, making it impossible to trace food back to its origin. This way of presenting trade statistics creates a problem for researchers and policy makers, trying to understand the food system and trade in food on a national level. This is a serious problem, and it would be desirable if statistics of food trade could be made more transparent in future.

The Swedish *foodprint* – Directly and indirectly appropriated area for food consumption in Sweden 1997-2000

Introduction

Yields have increased over time, making it possible to harvest more food per hectare agricultural area. However, there are no free lunches. Although food production has more than kept pace with population growth, it has done so at the expense of quality of soils, biodiversity, clean water and the carbon storage capacity. Land areas are degrading, making it necessary to take new area into production, converting forested and wetland area into agricultural area. Ecosystem services are dependent on area outside the agricultural area, in addition to the agro-ecological area.

Ecosystem services are 'the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfil human life' (Daily, 1997a). Biodiversity is the variety of life at all levels of organisation, from the level of genetic variation within and among species to the level of variation within and among ecosystems and biomes. The stability, functioning and sustainability of ecosystems depend on biodiversity. Evidence shows a strong dependence on biodiversity of the resistance of ecosystem functioning to disturbance, indicating that more diverse ecosystems are more stable (Tilman, 1997).

The food system is today highly dependent on fossil fuel for production and transportation of foodstuffs, so the ecosystems' work of sequestering excess CO_2 is of major importance. Our excessive use of fossil fuel is most probably increasing the greenhouse effect and thus global warming. To put another log on the fire, so to speak, forested area that is needed for sequestering the added carbon dioxide is being removed in large areas of the globe to produce more agricultural land, also resulting in extensive habitat and species loss. Areas lost due to soil degradation and areas for ecosystem services are appropriated indirectly by our food system to support our food consumption.

Indirect areas are often not accounted for in area-based studies of food consumption (Gerbens-Leenes & Nonhebel, 2002; Gerbens-Leenes, Nonhebel & Ivens, 2002; Cowell & Parkinson, 2003; Deutsch, 2004), except in ecological footprint studies (Wackernagel & Rees, 1996; Borgström Hansson & Wackernagel, 1999; Wackernagel, Lewan & Borgström Hansson, 1999).

Objective

The objective of this study was to visualise the land areas appropriated in addition to agricultural land area, appropriated *indirectly* by food consumption in Sweden.

The objective was also to broaden the window of attention, including the area needed for ecosystems support.

The objective was also to estimate the *foodprint* of Sweden, *i.e.* the total area needed, by adding the direct and semi-direct from the previous study *Agricultural area for food consumption in Sweden 1997-2000 – A study of the direct and semi-direct areas* to the indirect land area estimated in this present study.

Materials and methods

Data on soil degradation and ecosystem services from various published sources were analysed in EXCEL™ spreadsheets, together with data on Swedish food consumption from the earlier study of agricultural area in this thesis. This study differs from an EF-study in that equivalence factors were not used, see section od EF in Methodological framework. The attempt was to estimate the actual area of the foodprint. An explanation of data used follows.

Area appropriated by ecosystem services

1. Twelve percent of land for biodiversity

According to Wagernagel & Rees (1996) and the EF-methodology, an additional 12% of land use needs to be set aside for biodiversity. There is no scientific base for 12% being enough. Their figure in turn originates from The Brundtland Commission's report (1987) on our common future, which states that the 4% of the earth's land area managed explicitly to conserve species and ecosystems needs to be at least tripled.

The support area for biodiversity, following the EF-methodology by Wagernagel & Rees (1996), here termed *ecosystems area-12%*, was calculated using the following equation:

Ecosystems area-12% = (Direect area + semi-direct area)* 12%

2. Ecosystem services in organic agriculture

Since the area for biodiversity by the EF-method is so arbitrarily estimated, another approach is used to complement. A calculation is suggested using the difference between yields in organic farming and mainstream farming systems that are fairly similar, except for the use of external inputs used to compensate for ecosystem services that a larger area could provide. In Sweden, organic agriculture has on average 35% lower yields than mainstream farming (Statistics Sweden, 2004b), which corresponds with 20-40% lower yields in organic agriculture in the rest of Europe (Stockdale *et al.*, 2001). Lotter (2003) has found that organic agriculture yielded 10-15% lower than comparable conventional agriculture on average. However, this figure varies for different crops and depends on the production system one compares it to, *e.g.* a production system with low external inputs can have smaller yields than an organic production system with high external inputs. It has been noted that when organic farming is practised in many countries in the South, the yields *increase* in comparison to conventional farming, contradictory to what most often happens when farmers in then North change to organic farming. This is often due to organic farming being more managed than the most common family farming (Stockdale *et al.*, 2001; FAO, 2005). However, in this study this is disregarded since the non-organic farming systems that normally produce crops for export are different and more managed than the most common family farming.

The ecosystem support area, using the assumption above was calculated as a minimum, *ecosystems area (org-min)*, and maximum, *ecosystems area (org-max)*, using the following equations:

ecosystems area (org-min) = (Direect area + semi-direct area)*10%

ecosystems area (org-max) = (Direect area + semi-direct area)*40%

where 10% is a minimum decrease in yield (Lotter, 2003), and 40% is a maximum decrease in yields (Stockdale *et al.*, 2001) compared to mainstream farming in the counties mainly producing food consumed in Sweden.

3. Carbon dioxide assimilation due to fossil fuel use

Ecosystems area is needed due to energy consumption in the food system, mainly to sequester fossil carbon added to the active carbon cycle of the biosphere as carbon dioxide (CO_2) through burning of fossil fuel. The footprint for energy use was estimated using existing data (Singh, 1986; Folke *et al.*, 1997; Uhlin, 1997; Wackernagel, Lewan & Borgström Hansson, 1999).

Fossil energy land in a EF-study refers to the spatial impact of fossil fuel use and corresponds to the area needed for newly planted forest to sequester fossil carbon added to the active carbon cycle of the biosphere as carbon dioxide (CO_2) through burning of fossil fuel. This forest area then needs to remain untouched so as not to release the CO_2 again (Wackernagel & Rees, 1996). Wackernagel, Lewan & Borgström Hansson (1999) calculated the energy footprint as the area needed to sequester CO_2 from the use of coal, fossil oil, fossil gas and nuclear power, and the builtup area for hydropower. The nuclear power is calculated as if it was equal to fossil fuel. They calculated the area to be 2.3 ha per capita, which is equivalent to 20.7 million ha energy area for the whole country of Sweden. An earlier study by Folke *et al.* (1997) calculated the appropriated ecosystem area for sequestering CO_2 from energy use by the largest cities in the Baltic region. Assuming that the average Swedish consumer has the same energy footprint, gives a total of 19.9-48.9 million ha for sequestering CO_2. The lower end of this range is similar as the footprint area by Wackernagel, Lewan & Borgström Hansson (1999).

A minimum (*ecosystem area (energy-min)*) and maximum (*ecosystem area (energy-min)*) ecosystem area in this study was estimated using the following equation:

ecosystem area (energy-min) = energy area-min (19.9)*16.5%

ecosystem area (energy-max) = energy area-max (48.9)*20 %

where the food system is estimated to be responsible for 16.5% (Singh, 1986) to 20% (Uhlin, 1997) of the entire nation's energy use, giving a range, see Table 14.

Table 14. Energy area for food consumption, in ha and as a percentage of agricultural area. Maximum and minimum areas are given

	Energy area for food consumption maximum [c]	Energy area for food consumption minimum [d]	Percentage of agricultural area maximum [c]	Percentage of agricultural area minimum [d]
Ecological footprint[a]	4140000	3415500	111%	91%
Appropriated ecosystem area maximum[b]	9775385	8064692	261%	216%
Appropriated ecosystem area minimum[b]	3973846	3278423	106%	88%

[a] (Wackernagel, Lewan & Borgström Hansson, 1999)
[b] (Folke *et al.*, 1997)
[c] (Uhlin, 1997)
[d] (Singh, 1986)

Area lost due to soil degradation

The indirect area needed due to soil degradation was calculated by estimating how much new area needed to be appropriated to replace crop production lost because of area completely lost. New area appropriated to compensate for land with reduced production due to decreased yields is already included in the direct area calculations, since that degraded land is still within the agricultural system. The degradation rates are presented as the world average, and average for five global regions. Data for soil degradation were taken from IBSRAM (2001). Degradation is far from uniform in any region, and averages should be interpreted with care.

The degraded agricultural area for food consumed in Sweden was calculated using the following equation:

Degraded agricultural area = (Direct area + semi-direct area)* 0.5%

where 0.5% is the world average loss of agricultural land (IBSRAM, 2001).

Results

The Swedish *foodprint* was calculated to be about 2 to 4 times larger than the average agricultural area used for food consumption in Sweden 1997-2000, see Table 15. The *foodprint* was calculated conservatively, *foodprint*-min, and expanded, *foodprint*-max, by using several different sources of information. Direct land area appropriated for food consumption for 1997-2000 was on average 3.7 million ha for Sweden. Sixty five percent of this area was estimated to be in Sweden, and 35% abroad. Semi-direct land use for the same period as above was around 2-3% of the *foodprint*, *i.e.* 260 000 ha of fallow land. The indirect land use was estimated at 3.7 and 10.8 million ha for ecosystem services, depending on estimation approach, with around 19 000 ha of degraded land.

Table 15. Summary of footprint areas, total and per capita, for Swedish food system, that make up the ***foodprint***

	Total *footprint* (ha)	*Footprint* per capita (ha)
Agricultural land (direct land use)	3 739 206	0.42
Fallow land (semi-direct land use)	261 744	0.03
Ecosystems area-12%	448 705	0.05
Ecosystems area-organic	981 542	0.11
Ecosystems area (energy-min)	3 278 423	0.36
Ecosystems area (energy-max)	9 775 385	1.09
Land degradation	18 696	0.002
Indirect land use (min)	3 745 8240	0.41
Indirect land use (max)	10 775 623	1.20
***Foodprint*-min**	7 746 774	0.86
***Foodprint*-max**	14 776 573	1.64
***Foodprint*-average**	11 261 674	1.25

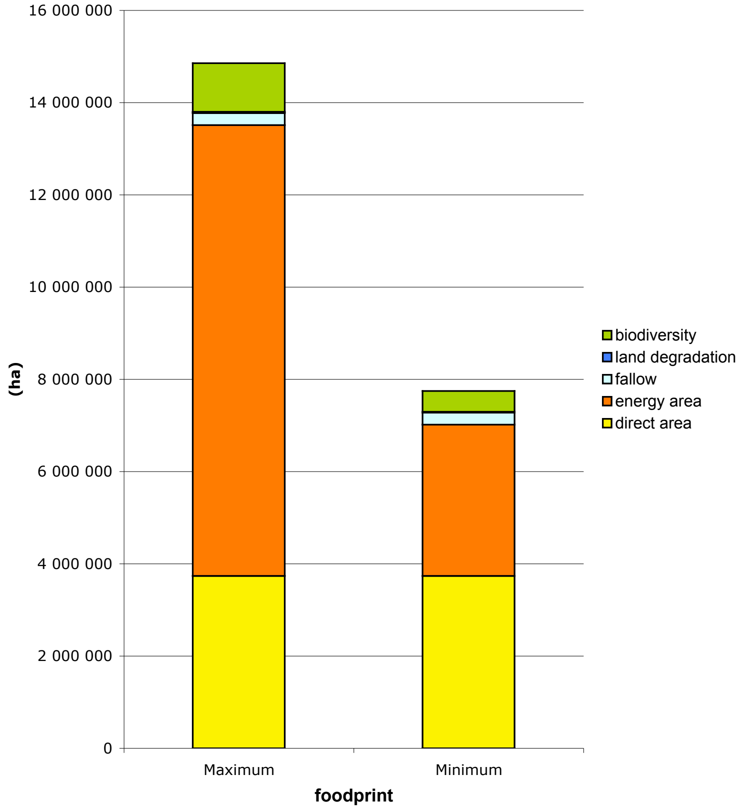

Figure 9. Comparison of maximum (14.9 million ha) and minimum (7.7 million ha) footprint

A direct area for fish was not included in this or the previous part of the study. Nevertheless, fish is still transported in the food system and included in the data used from published studies, and is therefore included in the energy footprint. For example, salmon is an important import and export commodity for Sweden.

Discussion

There is a trend that the higher the external inputs to the agricultural production system, the larger the yield. This in turn brings down the area needed to produce the same amount of food that a larger area with lower external inputs would produce. However, it is argued here that the smaller area, with high external inputs and large yield, also requires a larger indirect area, *e.g.* habitat for biodiversity, area for ecosystems services such as carbon dioxide sequestering, and new area needed due to land degradation. See the simplified model below.

High external inputs → large yield → small arable area + large indirect area
Low external inputs → small yield → large arable area + small indirect area

The indirect land use for ecosystem services and land degradation in this study vary between 100-292% of agricultural area appropriated for food depending on estimation approach, or 9-26% of total land area of Sweden. It has been asked often how much area is enough to protect biodiversity and ecosystem services (*e.g.* (Noss & Cooperrider, 1994; Main, 1999), however fewer have a precise answer to the question. The EF-methodology suggests 12% of additional area to the activity studied (Wackernagel & Rees, 1996). When comparing to others assessments, the largest critique of the EF-methodology may not be that it is arbitrary, but that it is so small. Noss & Cooperrider (1994) have converged various published estimates on how much of a country's total land area should be reserved to "maintain viable populations of large carnivores and sustain natural disturbance regimes", distributed optimally. They suggest that most regions will require 25-75 % of a country's total land area. This would mean that Sweden would require to set aside 10.3-30.8 million ha of its 41.1 million ha total land area. Considering that the focus of this thesis is on only one human activity, food consumption, the calculated area for ecosystem services in this thesis, 7.7-14.8 million ha, is quite high when compared. However, approximately one third of this area is outside our borders, due to our food imports.

The areas calculated for biodiversity in this thesis, *ecosystem area-12%* (448 705 million ha) and *ecosystem area-org* (981 542 million ha), may not necessarily be alternative, but also, at least partially, additive. Adding them together, together with an average of *ecosystem area (energy-average)* gives an area for ecosystem support of 8.0 million ha, 19% of total land area.

The area for land degradation is small in this context, see Figure 9. Although, when the data are presented on an area basis of about 19 000 ha, as in Table 15, and not as a percentage of the total *foodprint*, the area is still substantial. One must also remember that this area is most likely lost entirely for food production, at least for several generations to come. The severity of soil degradation in not captured in an EF-study. Large areas of arable land have been degraded in quality, even if not in quantity. Degradation in quality lowers the efficiency of use of inputs and increases risk, and this is not captured in the data presented above. More weeding is required, replanting or reseeding is sometimes needed, fertilisers are lost in runoff, products are of lower quality and crops fail in some years due to degradation in land quality. Larger quantities of inputs such as fertilisers, pesticides and irrigation are needed to compensate (Langdale *et al*., 1992). Not only are these inputs fossil-energy dependent, but they also harm human health and pollute the environment (Pimentel *et al*., 1999; IBSRAM, 2001). Although the indirect land area for land degradation is small in relation to the other indirect areas in this study, this should not be interpreted that land degradation is not an important area to consider. It is probably more a result of the other areas for ecosystem services not having been considered sufficiently in studies until recently.

These indirect areas cannot be calculated exactly, which may be a contributing factor to why they are often excluded in studies. I do not claim to give exact calculations of indirect area in this study. However, I claim that there is a need to *try* to visualise these areas in order to investigate what we can do to make unsustainable trends change for future food security. Footprint studies are very visual. However, there is more than meets the eye in even an ecological footprint (EF). A lot of goods and services, supporting the food system are not included in an EF-study and a holistic method that has the ability to account for all previous work, both by nature and man, necessary to generate food consumption is needed.

Emergy synthesis and emergy footprint of the Swedish food system 1996

Introduction

The *foodprint* was estimated to be between 7.7 and 14.9 million ha in the previous chapter of this thesis. However, ecosystem support and environmental load is more than just sequestering excessive CO_2 and a habitat for biodiversity. Sustaining a carrying capacity for a population and its activities, *e.g.* consuming food, requires that there is a balance between the use of environment as a source of resources and its use as a sink for wastes. The concept of carrying capacity relates resource use to environmental support (Wackernagel & Rees, 1996; Brown & Ulgiati, 1998). According to Brown *et al.* (2000) carrying capacity is related to the ability of a local environment to provide necessary resources for a population, or economic endeavour, on a renewable basis. In emergy terms, the long term carrying capacity of an area is limited by the flux of renewable emergy that is characteristic of that area (Brown *et al.*, 2000). The direct and indirect land use based on emergy is similar to the concept of 'ecological footprint' in that it relates resource use to an area (Geber & Björklund, 2002). The difference is that when the land use is based on emergy, resources that are not directly tied to an area demand, such as farm buildings, machinery and other infrastructure, can be included and consistently converted to the amount of environmental support needed to generate them. This means that an area demand based on emergy use will give a more far-reaching comparison of the actual area needed for different activities (Brown & Ulgiati, 1998; Geber & Björklund, 2002). This also means that the area can be very large for a system that uses resources produced over a long time period and/or large external area, as in the case of fossil fuel. An emergy footprint further develops the *foodprint* approach by tracking the total resource network converged and transformed within the Swedish food system, using solar emergy as a common basis for accounting.

Objective

The objective of this study was to account for environmental services appropriated by the Swedish foodsystem by using emergy synthesis. The objective was also to calculate the support area for the Swedish food system, from the primary production on the farm to the household preparation of food, by calculating the *emergy footprint.*

Materials and methods

Emergy synthesis

This systems study further develops the foodshed concept (Kloppenburg, Hendrickson & Stevenson, 1996) by tracking, in aggregate, the total resource network converged and transformed within the Swedish food system, using solar emergy as a common basis for accounting. Methods follow Odum (1996) and are described in Methodological framework. Quantitative information on environmental parameters, resource-use, labour and market subsidies supporting the Swedish food system in 1996 were assembled from published literature and national statistical abstracts. Baseline data, reported as available energy (J), mass (kg), or dollars (USD) required to generate annual output quantities of various food items, were compiled and summed for each sector. Citations and computations are referenced as footnotes in appendix A corresponding to line item numbers in tables and similarly noted in the text. Estimates and assumptions stemming from inadequate or unavailable data are also stated in footnotes in appendix A.

The synthesis is organised into four process sectors of the Swedish food system following Andersson (1998): 1) farm production; 2) processing; 3) distribution; and 4) consumption. The consumption sector does not include waste management, housing or kitchen equipments. Import and export food products were also evaluated. Resource data are converted into solar emergy, often abbreviated solar emjoules (*sej*), using referenced transformation ratios (*sej*/J, *sej*/kg, or *sej*/USD) and aggregated for input variables (F_i) and output quantities (J_i) corresponding to each of 4 sectors (i). Estimates and calculations of resources supporting direct labour and indirect human services supporting purchased goods are also footnoted.

The emergy calculations in this study, used to calculate the emergy footprint, have been presented in an earlier publication *Swedish food system analysis 1996* by Johansson, Doherty & Rydberg (2000) at the conference: *Emergy Synthesis: Theory and Applications of the Emergy Methodology. First Biennial Emergy Analysis Research Conference*, in Gainesville, Florida, in September, 1999. The transformities used in calculations are based on the emergy baseline data prior to 2000, and do not reflect the amendment of new tidal momentum absorption (Campbell, 1999). To compare this study with more recent studies, all flows should be multiplied by 1.68, as suggested by Odum (2000).

Emergy indices and ratios

Indices and ratios were calculated for resource-use (F_i) within and between sectors (i) and for production output (J_i) following Odum (1996) and Brown and Ulgiati (1997). Indices and ratios are used to facilitate comparisons and to generate perspectives.

The emergy yield ratio (EYR) quantifies net benefit of feedback investment to a nation, region or a process, in this study food consumption. EYR is the ratio of emergy output (Y) to investment (F) to secure an output, in this study food:

$$EYR = Y/F$$

where Y = food and F = all investment inputs, e.g. fuels, fertilisers, and other goods and services from outside the food system. When this ration exceeds 1, investment is beneficial (Brown & Ulgiati, 1997).

The environmental loading ratio (ELR) states the ratio of non-renewable and purchased resources (N, F) to local renewable (R) describing the load on the environment.

ELR = (N+F)/R

ELR indicates the pressure from the process on the local ecosystem and can be considered a measure of the ecosystem stress due to production activity, and of the ability of the process to exploit local resources (Brown & Ulgiati, 1997).

The transformity can also be seen as an indirect measure of how much activity of the environment, the direct and indirect environmental support, that has been required to manufacture a given product, in this study food. In essence, the higher the transformity of a resource the greater the environmental activity necessary to produce it (Brown & Ulgiati, 1997).

Emergy footprint

A methodology, as used by Brown & Ulgiati (1998) and Geber & Björklund (2002), was used to calculate an emergy footprint. The emergy footprint factor (EFF) was calculated using the formula:

EFF = R / Agricultural area of Sweden

where R is the local, renewable resources in emergy (1.29E+21sej/yr). In this study R was the emergy in the part of the rainfall that was evapotranspirated. The agricultural area used in 1996 in Sweden was 3.6 million ha. For the Swedish agricultural area, EFF is 3.6E+14 sej/ha and year. Brown and Ulgiati (1998) calculated the average global EFF to be 1.85E+14 sej/ha and year. The global average is about half that for the Swedish agricultural area, which is reasonable since global area includes large areas with little or no rainfall, *e.g.* barren regions and desert areas with less ability to embody solar energy. The emergy footprints for the whole food system supporting food consumption in Sweden, as well as for the sub-systems themselves, were calculated by multiplying 3.6E+14 sej/ha (EFF) by the emergy use for each sector.

Results

Emergy synthesis

The resource basis of the Swedish food system of 1996 was analysed using emergy as a measure of direct and indirect resource support and environmental load (Johansson, Doherty & Rydberg, 2000). Results from this study show that as much as 89% of resource use in the food system involves purchased resources (F_i), *e.g.* fuel, electricity, fertilisers and machinery. Most of these resources are of non-renewable origin. Furthermore, 8% of resource use was local non-renewable (N), in this case a decrease of soil organic matter in crop production. This leaves only 3% of resource use in the Swedish food system to be local renewable (R), implying that food consumption is highly dependent on non-renewable resources.

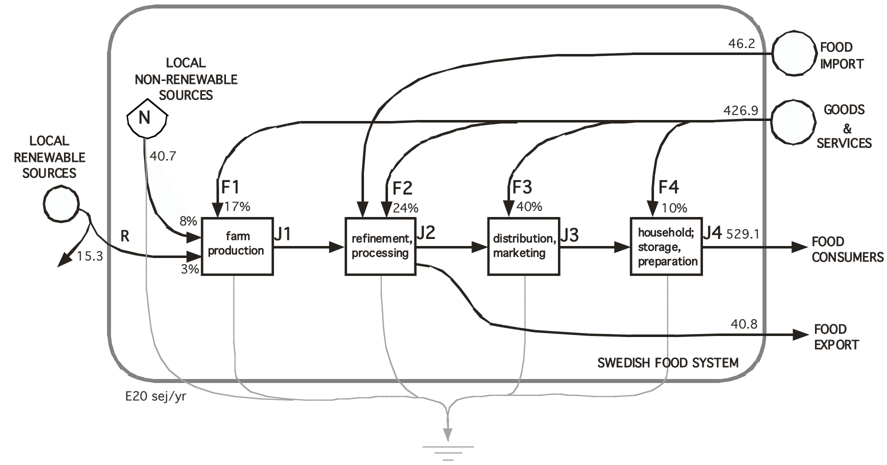

Figure 10. Aggregated systems diagram of the emergy flows supporting food consumption in Sweden, 1996. Variables are defined in Table 16 and summarised in Table 17. Resource inputs (R, N, Fi) from outside the food system frame are reported as E20 sej/yr, and inside the frame as percentage of resources used in the food system (529.1E20 sej). Rounding to whole numbers results in slight overestimates.

Table 16 details inputs, identified by line items, to the Swedish food system, organised within process sectors (F_i) and summed for food product output (J_i). *Local renewable sources* (R) includes direct solar insolation over cultivated lands and greenhouses (item 1), and annual precipitation allocated to evapotranspiration (item 2) or runoff (item 3). *Local nonrenewable resources* (N) includes loss of soil organic matter on cultivated lands (item 4). *Farm production* (F_1) includes inputs supporting cultivation, management and harvesting for agriculture, horticulture and fisheries (items 5-15); *industrial processing* (F_2) includes refinement and packaging inputs (items 20-25); *distribution* (F_3) includes inputs to wholesale and retail markets (items 26-31); *consumption* (F_4) includes fuels and electricity used in storage and preparation in the household (items 32-34). Transportation costs are allocated within each sector. Import foods are added in and export foods are subtracted from the food system to account only for the food consumed domestically.

Table 16. Food system supporting Swedish food consumers 1996. For footnotes, see Appendix A

Item-note		component	data (J, kg, USD)	conversion (sej/unit)	solar emergy (E20 sej/yr)
R		Renewable resource-use:			
	1	Solar insolation	8.27E+19 J	1	0.83
	2	Rainfall, evapotranspiration	7.09E+16 J	1.8E+04	12.91
	3	Rainfall, runoff	5.77E+15 J	2.8E+04	1.60

N	Non-renewable resource-use:				
	4 Soil organic matter	5.65E+16	J	7.2E+04	40.69
F_1	Purchased resource-use in farm production:				
	5 Fuel	1.36E+16	J	5.6E+04	7.63
	6 Electricity	5.30E+15	J	1.3E+05	6.73
	7 Pesticides	1.61E+09	g	1.5E+10	0.24
	8 Calcium oxide	2.12E+08	kg	1.0E+12	2.12
	9 Potassium fertilizer	4.24E+07	kg	1.1E+12	0.47
	10 Nitrogen fertilizer	1.92E+08	kg	3.8E+12	7.31
	11 Phosphorous fertiliser	2.13E+07	kg	3.9E+12	0.83
	12 Machinery	4.93E+08	USD	1.2E+12 [a]	6.06
	13 Buildings	8.96E+07	USD	1.2E+12 [a]	1.10
	14 Direct labor	1.53E+08	hrs	4.7E+12 [b]	7.04
	15 Indirect services [c]	3.99E+09	USD	1.2E+12 [a]	49.05
	J_1 Farm food products:	9.22E+16	J	1.6E+05 [d]	144.61
	J_{Ex} Export food:	1.69E+16	J	2.4E+05 [e]	40.81
	J_{Im} Import food:				
	16 Meat	2.76E+14	J	1.7E+06	4.78
	17 Fish	5.84E+14	J	3.5E+06	20.44
	18 Sugar	1.42E+14	J	8.5E+04	0.12
	19 Other	3.06E+16	J	6.8E+04	20.84
F_2	Purchased resource-use in processing:				
	20 Fuel	7.20E+15	J	5.6E+04	4.04
	21 Electricity	8.73E+15	J	1.3E+05	11.09
	22 Machinery	4.57E+08	USD	1.2E+12	5.62
	23 Buildings	1.20E+08	USD	1.2E+12	1.47
	24 Direct labor	6.09E+07	hrs	4.6E+12 [b]	2.80
	25 Indirect services [c]	6.48E+09	USD	1.2E+12 [a]	79.71
	J_2 Processed food products:	8.26E+16	J	3.3E+05 [f]	269.02
F_3	Purchased resource-use in food distribution:				
	26 Fuel	1.08E+16	J	5.6E+04	6.06
	27 Electricity	1.33E+16	J	1.3E+05	16.92
	28 Machinery	2.22E+08	USD	1.2E+12	2.73
	29 Buildings	9.79E+07	USD	1.2E+12	1.20
	30 Direct labor	9.94E+07	hrs	4.6E+12 [b]	4.62
	31 Indirect services [c]	1.45E+10	USD	1.2E+12 [a]	177.82
	J_3 Food products at markets:	8.02E+16	J	6.0E+05 [g]	478.36
F_4	Purchased resource-use in food preparation:				
	32 Fuel	9.80E+15	J	5.6E+04	5.50
	33 Electricity	2.58E+16	J	1.3E+05	32.83
	34 Indirect services [c]	1.01E+09	USD	1.2E+12 [a]	12.45
	J_4 Consumed food products:	7.05E+16	J	7.5E+05 [h]	529.14

Table 17 and Figure 10 summarise the synthesis. Local, renewable sources (R) contributed 11% of resources supporting domestic farm production (J_1) and only 3% of all food system resources supporting final consumption (J_4). Soil organic matter used up (N), constituted 73% of local resources (R+N), 28% of resources used in farm production (J_1) and 8% of food system resources. The economic component of the whole food system (F_{1-4}) thus accounted for 89% of total resources used (Y). Resources used in imported foods were estimated at 9% of total food system resources. Import and export foods each used about 15% of resources in production and processing ($F_{1\text{-}2}$).

Table 17. Resource use summaries of the Swedish food system 1996

Components	Emergy (E20 sej/yr)	% of total agricultural production	% of total food system
Local environmental resources (E = R+N):	56.0	39	11
R Local renewable resources	15.3	11	3
N Local non-renewable resources	40.7	29	8
F_1Purchased resources for agricultural production	88.6	61	17
Total resource use in agricultural production	185.3	100	28
Food trade			
Import food products	46.2		17
Export food products	40.8		15
F_2Refined, processed food	124.4		24
F_3Food delivered to markets	209.3		40
F_4Prepared food for consumption	50.8		10
Total resource use in whole food system (Y = E+F):	529.1		100

The distribution and marketing sector (F_3) required the greatest quantity of purchased resources (40% of total), followed by the processing sector (F_2) using 24%. Farm production (F_1) and consumption (F_4) required fewer resources (17% and 10%, respectively). Resources required for food sector products (i.e., solar transformity) increased almost 5 fold from 1.6E+5 sej/J for farm products to 7.5E+5 sej/J for consumed foods. Indirect services supporting purchased goods were greatest for processing and distribution (76% and 85% of sector total, respectively), and lowest for farm production (55%) and consumer end-use (25%). Fuels and electricity were intermediate demands within food sectors. Local labour was highest in the farm production sector, measured both as labour-hours employed and as per cent of sector resources (F_i).

Emergy indices and ratios

The greatest percent increase in food product transformities was between farm products (J_1) and processed foods (J_2) and lowest between market products (J_3) and consumer foods (J_4), see Table 18. Environmental loading (ELR_i) increased with additional purchases supporting each food product sector, with the greatest percent difference between farm production and processing (96%) and lowest between distribution and consumption sectors (10%). Environmental loading (ELR_1) of 8.5 was calculated at the farm level, with a disproportion of purchased goods (F_1) and soil loss (N) relative to local environment (R). Overall, economic investments (F) used in the whole food system measured almost 8.5 times greater than local environmental sources (E), loading the environment more than 30 to 1 by the time food products are processed, distributed, and consumed. This trend is also evidenced in the declining yields (EYR_i) measured between food sectors.

Table 18. Emergy indices and ratios for the Swedish food system 1996. Percent difference of index values between sectors are given in parentheses. References to J_i can be found in Figure 10 and Table 16

	Farm products (J1)	Processed food (J2)	Market products (J3)	Consumed food (J4)
Solar transformity (E5 sej/J)	1.57	3.26 (+108%)	5.97 (+83%)	7.50 (+26%)
EYR	1.6	1.3 (-19%)	1.1 (-15%)	1.1 (+/-0%)
ELR	8.5	16.7 (+96)	30.4 (+82%)	33.4 (+10%)

Emergy footprint

The Swedish food system of 1996 in its entirety was found to be supported by an emergy support area of more than 140 million ha, see Table 19. In accordance, the emergy footprint was more than 40 times the direct agricultural area supporting food consumption in Sweden. Almost one quarter of the emergy footprint supported the agricultural production. *i.e.* ten times the direct agricultural area. Food distribution in markets and grocery stores needed the largest emergy support area, with 40% of the total emergy footprint.

Table 19. Emergy footprint for resource use by different sub-systems in the food system, and for total resource use for food consumed in Sweden 1996

Sub-system in food system	Emergy (E20sej/yr)	Emergy footprint (million ha)*	Emergy footprint (ha/ha direct arable land)**	% of total emergy footprint
Direct agricultural land			1	2.5
Agricultural production	135	37	10	25
Food processing	105	29	8	20
Food distribution	209	58	16	40
Food consumption	51	14	4	10
Total emergy in consumed food products	512	147	40	100

* emergy footprint factor is 3.6E+14 sej/ha

** emergy footprint divided by direct agricultural area of 3.58 million ha

Discussion

The food system index values from this study are compared with national index values for 1996 (Lagerberg et al, 1999) in order to place the results of this study into a national context. The Swedish food system invests almost 3 times as much purchased resources relative to local environmental support than the national aggregate resource use. Environmental loading (ELR) resulting from production of consumer foods (J_4) measured almost 5 times greater than the load generated at the national level (33.4 compared with 6.8). These indicators equate consumer food products with high quality commodities. In fact, resource-use per economic product for the food system measured 1.5 times greater than the same national index. Food sustainability would require resource-use (solar transformity) below the national average for economic and industry activities and higher net yields (EYR). This finding is also in accordance with the ecosystem area for the food system in the previous study being large, 19% of land area, in comparison to the ecosystem area for all activities conducted in the country, suggested to be 25-75% (Noss & Cooperrider, 1994).

This synthesis identifies that contributions from local labour and environmental support are small relative to fuels, purchased goods and indirect services. With food prices influenced by consumer preference, profits enlarge at markets and intermediate sectors, where indirect services are greatest, restricting farm income and drawing attention away from necessary environmental support. Subsidies may increase inefficiencies if investments are directed at accelerated production to meet market demands and not environmental limits. Because farm products are refined and transformed into consumer goods and widely distributed to markets far from the source of production, food prices and resource-use may be inflated above minimum costs and requirements.

Two food sectors integral to basic human sustenance (farm production and food preparation) require fewer resources than sectors involved in food commoditisation (processing and marketing). Environmental loading is correspondingly higher for intermediate sectors. While local direct impacts may be minimal and may even be reduced through local actions (*e.g.* organic farming), indirect impacts are generated at regional, national and global scales where human services supporting intermediate food product sectors are based. A consequence may be that responsible actions by producers and consumers are lessened by the economic engines of industry and markets.

Until recently, food production relied on local and ecological knowledge. Education in food storage and preparation, offered within communities for farms and families, are no longer common. Industry and markets have obfuscated food production boundaries and diluted the role of local institutions. Emerging service economies have drawn workers away from rural areas, extending families and consumers beyond their communities and diminishing the need for local knowledge. Because agriculture is biophysically linked to environmental limits, management efforts, fuel and agro-chemical subsidies have diminishing returns to production. Efforts toward sustainable food supplies should base delivery on environment and farm production capacities. Other actions include reducing intermediate sector demands, transport distances and indirect services, and increasing institutions, labour, and knowledge supporting farms and local ecosystems. Reconnecting production and consumption of local foods could be an important step toward food system sustainability.

This study provides further evidence that the area needed to support Swedish food consumption is extensive, to say the least. The emergy support area is a massive forty times the agricultural area, 3.6 times the land area of Sweden. What does this mean? What is this area? When studying a system like agriculture, which uses a high degree of external inputs high in emergy, the emergy support area becomes large since it takes a large area to concentrate the solar energy. When the system also uses fossil fuels and metal ore built into technomass, which have been produced over a massive time period of several million years, the emergy support area also becomes a 'historical' area. The resources Swedish food consumption used in one year took many more years to produce, but are here transformed to an yearly basis and a common area.

The first sub-system, agriculture, was supported by an area ten times that of the agricultural area. Even this is a large area, and provides a hint that Sweden would need much more area if it wanted to, or had to, produce the same agricultural products using only local renewable resources. Sweden does not have this much agricultural area available today within its borders and, as shown in earlier sections of this thesis, it is already using more than is available per global citizen. This also provides evidence that Sweden needs to review current consumption patterns and the choices made by consumers at the grocery store. Changing consumption patterns could decrease Swedish resource use.

Summary and discussion

In the first part of the study, *Agricultural area for food consumption in Sweden 1997-2000 – The direct and semi-direct area*, I found that food consumption in Sweden is dependent on an agricultural area of 3.7 million ha, mostly arable, corresponding to 0.41 ha per capita. This is one and a half times more than the average of 0.27 ha arable land per capita on a global scale. It must also be noted that the relationship between the more productive arable land and the land mostly suited only for grazing is in favour of Sweden when compared with the rest of the world. With a growing world population, the average available agricultural area is estimated to be 0.19 ha per capita in the year 2025 when we will be around 8 billion people in the world. In 1960, the average available agricultural area was 0.46 ha per capita.

However, earlier studies have shown that analysing only the agricultural area can give a false impression of living within our limits and being efficient in our food production. Deutsch (2004) shows us how our appropriated agricultural area has decreased from 1962 to 1994. Does this mean our food production has become more efficient? Does it mean we actually need less ecological space for our food production today? From the 1950s to the 1990s we not only had a decrease in appropriated agricultural area, but we also had an increase in external inputs, mostly non-renewable inputs. We have moved from a more low input to a more high input agriculture, with local ecological goods and services being replaced by fossil fuel-driven technology (Björklund, Limburg & Rydberg, 1999). They show that about 20% of Swedish agricultural land has been taken out of production during the past 40 years. One may even start to wonder if there is such thing as a *more efficient* agriculture. The total amount of energy used in two different systems, each producing the same product but in two different times, may be the same, but using different energy transporters; one being fossil fuels and another horse feed (Rydberg & Jansen, 2002). In the latter case more area was used, and in the former more external inputs were used per area unit. However, the systems produced very similar yields per resource unit calculated as emergy.

Ecosystems services have gained recognition and appreciation through efforts to substitute technology for them. 'Society is likely to value more highly these services as human impacts on the environment intensify and the costs and limits of technological substitution become more apparent' (Daily, 1997b). In order for 3.7 million ha to support us with food, a certain amount of external inputs has been used, and a certain amount of ecosystems services has been appropriated. How much area do these ecosystem services need? How do we know not to degrade these areas, that may be our saving in a future with less fossil fuels? An attempt to calculate indirect land use for ecosystem services and to compensate for degraded land was made in the study *The Swedish foodprint – Directly and indirectly appropriated area for food consumption in Sweden 1997-2000*. The area for ecosystem services varied between 3.7 and 10.8 million ha, or 0.41 and 1.2 ha per capita, depending on the estimation approach. Both area for sustaining biodiversity and area sequestering CO_2 from use of fossil based fuels were estimated. The large difference is probably a reflection of how uncertain it is to calculate these areas. It is not possible to locate the CO_2 uptake to a certain area. Growing plants sequester CO_2 wherever they are; in a spatially covered grass lawn as well as in a dense forest. Even algae in the sea sequester CO_2, so the calculated areas are not really an exact calculation of the land area needed for these ecosystem services, more a pedagogic way to show *that* these areas may be large and making it possible to *compare* different human activities and their impact on our surrounding environments. The area for CO_2 uptake was estimated using two different existing and published calculations for Sweden (Folke *et al.*, 1997; Wackernagel, Lewan & Borgström Hansson, 1999). Both studies calculated how much forested area would be needed for the CO_2 sequestering. One of these studies had calculated a minimum and maximum area for CO_2 uptake (Folke *et al.*, 1997). The area for CO_2 uptake in the second study used was within the span of the first one, so I feel fairly confident that the answer lies somewhere around there.

New land area needed to compensate for degraded land was calculated to be 19 000 ha. In the context of the larger area for CO_2 uptake and biodiversity it may seem small, less than 1% of the *foodprint*. In spite of this, I would like to stress that this is more an indication of the energy area being much larger, and not the degraded area being small. The degraded area was of a different quality, with a much higher potential to produce food and other crops. It is also a much more serious loss since the quality of the land is lost, not just the quantity. Arable land has taken a long time to build up its fertility, *i.e.* organic matter, structure, water-holding capacities, *etc.* This is one example of the *foodprint* approach, much like many other footprint approaches, being very flat. There are different qualities on different lands. This study investigated the ecological footprint approach, here adapted to suit studying food consumption. White (2000) has calculated the ecological footprint of food, and he argues that analysing the use of environmental services of food consumption gives a better analysis of inequity than analysing for instance caloric consumption. For example, while the average North American consumed about 50% more calories than the average African in 1995, the North American's diet generated approximately 175% more environmental impact than the African's diet.

Virtues such as soil quality are captured in an area-based study. However, it is not obvious for the viewer. Decrease in yields lead to a larger footprint since more agricultural area is required. Furthermore, decrease in soil quality often lead to more external inputs used to compensate, however these may not show up entirely in the footprint if the method cannot appreciated the whole support required. Sustainability issues of social kinds are not addressed. Some things just cannot be translated into area use. Qualitative intrinsic values are missed. The footprint methodology, even when broadened to a *foodprint*, is very flat in a double sense since it also does not reveal where the area is. Ecological footprint (EF) is most often so anonymous that people do not know what to do with the information obtained. They consume more than their fair share, but where is this? What can they do? People run the risk of being overburdened by facts, and stay inactive. EF needs to be followed up by a constructive discussion on what can be done. So why use footprinting methods when they cannot show the truth? Evaluating footprint areas gives a different message than metric volumes or monetary values. Sometimes seeing something a different way may make us act differently. But what do we do with the qualities and impacts that are not captured in the *foodprint*?

The emergy synthesis includes all the resources needed to produce a good or service. The study *Emergy synthesis and emergy footprint of the Swedish food system 1996* provides further evidence that there is more to it than what first meets the eye, that the area needed to support Swedish food consumption is extensively larger than the direct agricultural area of 0.41 ha per capita, and that of the actual *foodprint* area, including the indirect areas, is 0.86 to 1.64 ha per capita. The emergy support area is a massive forty times the agricultural area, 16.6 ha per person. This area includes the historic area needed to produce the resources used for Swedish food consumption. In contrast to the *foodprint*, the emergy footprint gives an idea not only of the impact that follows the use of non-renewable resources, but also an idea of how much area we would need if we had to base the same system, our food consumption, on renewable resources.

No other published emergy footprints of the food system has been found. However, a comparison could be made with the area humans were reliant on when our diets were based on hunting and gathering. Buringh (1989) estimates that in general about 80 ha of land were needed to feed one person in a hunter-gatherer society, *i.e.* food produced only on local renewable resources by ecosystems services, using no external inputs for consumption. *Homo sapiens* are omnivores, which means that we can sustain ourselves on everything that has a nutritional value and is not poisonous to us. This could be fortunate for us in a future when we may need to change our consumption patterns. A nutritious diet that requires more land and resources than is available, will not improve food security. It was estimated that a consumption pattern modified as suggested by nutritionists to be healthier and more environmentally friendly would decrease the agricultural area by 14%. This may not seem much. However, it suggests that there is scope to decrease area at the same time as resource use is lowered by a change in what we eat. The modified diet is also just a first step, and the next step may lower the area even more. On the other hand, a more sustainable diet may need more direct area to compensate fossil-based external inputs with ecosystem services.

Concluding remarks

In this thesis I coined the term *foodprint* in an attempt to visualise our dependency on environmental support for food consumption. The results of this thesis show that there is much more than what first meets the eye.

In looking over a field of wheat one may have an idea or impression of how much area is required to produce a certain amount of bread *(Agricultural area for food consumption in Sweden 1997-2000 – A study of the direct and semi-direct areas)*. In the following year one may see the same field looking even better and producing even more wheat because of the farmer's investments in better wheat varieties and/or increased external inputs (*e.g.* fertilisers, pesticides, traction). However, the agricultural land is just the tip of the iceberg. While it is true that external resources can be used to increase yields in agricultural production, the true efficiency of these improvements can only be understood by accounting for the land areas that support these external resources. The results of my analyses demonstrate that the areas indirectly required are in fact larger than the field itself (*The Swedish foodprint – Directly and indirectly appropriated area for food consumption in Sweden 1997-2000*).

Since almost all food is so obviously derived from land it has perhaps been too easy to evaluate food systems with just footprint studies. However, more technical products, such as mobile phones or cars do not share this dilemma. But, this study shows that food consumption is indeed extremely dependent on technology and resources from society. The food we consume is today supported by a large, global food system, and it might help if it was regarded as a highly industrial product *(Emergy synthesis and emergy footprint of the Swedish food system 1996)*. We as a society must move towards measures that incorporate the environmental work invested in the food we consume, in order to develop sustainable food systems.

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Appendix A

Table 16 Footnotes:

a. Food system resources (529.1E20sej) measured 15% of national resource base, 1996 (3598E20 sej; Lagerberg et al 1999). National sej/GDP was reduced proportionally to estimate supporting indirect human services within the food system: (1.44E12 sej/USD, 1996; Lagerberg et al 1999)*(0.85) = 1.2E12 sej/USD
b. (4.07E+16 sej/p-yr; Lagerberg et al 1999) / (365 days/yr) / (24 hrs/day) = 4.65E+12 sej/hr
c. Economic costs of production within sectors F1, F2, F3 and F4 (items 1.15, 1.25, 1.31, 1.34) are proportioned to cost of food products sold to consumers from known costs and percentages.
d. $(R+N+F_1) / J_1$ = (144.6E20 sej) / (9.22E16 J) = 1.6E+05 sej/J
e. Solar transformity for export foods, J_{Ex}, estimated as average for farm food products (ST_1, item d) and processed food products (ST_2, item f).
f. $(R+N+F_1+F_2) / J_2$ = (269.0E20 sej) / (8.26E16 J) = 3.3E+05 sej/J
g. $(R+N+F_1+F_2+F_3) / J_3$ = (478.4E20 sej) / (8.02E16 J) = 6.0E+05 sej/J
h. $(R+N+F_1+F_2+F_3+F_4) / J_4$ = (529.1E20 sej) / (7.05E16 J) = 7.5E+05 sej/J

1. Solar insolation received on arable land, grazing land and greenhouses = 3.58E+10 [m^2, land area] (Statistics Sweden, 1997b, 1997c) x 8.50E+01 [$kcal/cm^2$, insolation] (Eggertsson-Karlström, 1998) x 0.35 [% albedo given as a decimal; average for bare soil, meadows, fields, snow covered ground] (Sellers, 1965) x 10000 [cm^2/m^2] x 4.19E+03 [J/kcal] = **8.27E+19 J**. Solar transformity by definition 1 sej/J.
2. Chemical potential energy of evapotranspired rainfall on arable land, grazing land and greenhouses = 3.58E+10 [m^2, land area] (Statistics Sweden, 1997b, 1997c) x 0.73 [m, precipitation] (Brandt et al, 1994) x 0.55 [% transpiration given as a decimal] (Sveriges Nationalatlas, 1995) x 1000 [kg/m^3, water density] x 4.94E+03 [J/kg, gibbs free energy] = **7.09E+16 J**. Solar transformity from Odum (1996).
3. Geopotential energy of runoff on arable land and grazing land = 3.58E+10 [m^2, land area] (Statistics Sweden, 1997b, 1997c) x 0.329 [m, runoff] (SMHI, 1994) x 5 [m, mean elevation] x 1.00E+04 [kg/m^3, water density] x 9.80 [m/s^2, gravity] = **5.77E+15 J**. Solar transformity from Odum (1996).
4. Organic matter lost on arable land = 2.50E+12 [g] (Johansson, 1998; Lilliesköld & Nilsson, 1997) x 5.4 [kcal/g] x 4186 [J/kcal] = **5.65E+16 J**. Solar transformity from Odum (1996).
5. Fuel used at farms for heating and machine use = 3.82E+08 [l, fuel] (Uhlin, 1997; Statistics Sweden, 1997b) x 3.56E+07 [J/l, energy content] = **1.36E+16 J**. Solar transformity from Lagerberg, et al (1999). Data on fuel-use for heating greenhouses not included.
6. Electricity used in agriculture, forestry and fisheries (Statistics Sweden, 1998e)= **5.30E+15 J**. Solar transformity from Lagerberg, et al (1999). Electricity-use data for forestry was included with agriculture and fisheries data and was not excluded here.
7. Pesticides used in farm production = 1.53E+09 [g, agriculture use] (Jordbruksverket, 1997) + 7.65E+07 [g, horticulture use; estimated at 5% of agriculture use] = **1.61E+09 g**. Solar emergy per mass from Brown & Arding (1991).

8. Calcium oxide sold to the agricultural and horticultural sectors = **2.12E+08 kg** (Statistics Sweden, 1998a). Solar emergy per mass from Odum (1996).
9. Potassium fertilizer sold to the agricultural and horticultural sector = **4.24E+07 kg** (Statistics Sweden, 1997b). Solar emergy per mass from Odum (1996).
10. Nitrogen fertilizer sold to the agricultural and horticultural sector = **1.92E+08 kg** (Statistics Sweden, 1997b). Solar emergy per mass from Odum (1996).
11. Phosphorous fertilizer sold to the agricultural and horticultural sector = **2.13E+07 kg** (Statistics Sweden, 1997b). Solar emergy per mass from Odum (1996).
12. Tractors, machinery and tools used = 3.30E+09 [SEK] (Statistics Sweden, 1997b) x 6.70 [SEK/USD, 1996 exchange rate] = **4.93E+08 USD.** Multiplier = solar emergy per GDP (note a).
13. Building construction and maintenance = 6.00E+08 [SEK] (Statistics Sweden, 1997b) x 6.70 [SEK/USD, 1996 exchange rate] = **8.96E+07 USD.** Multiplier = solar emergy per GDP (note a).
14. Labour hours in agriculture, horticulture, fishing and hunting = 6.80E+04 [people working] (Statistics Sweden, 1997b) x 45 [hrs/week] (Statistics Sweden, 1997b) x 50 [weeks/yr] = **1.53E+08 hrs**. Multiplier = solar emergy per hour (note b).
15. Expenditures for purchased resources used in agriculture, horticulture and fisheries = 1.67E+11 [SEK, cost of consumed food] (Statistics Sweden, 1997b) x 0.16* [% of cost, given as a decimal] / 6.70 [SEK/USD, 1996 exchange rate] = **3.99E+09 USD.** Multiplier = solar emergy per GDP (note a).

J_1 Farm food products = 7.13E+16 [J, agricultural crops]+ 2.03E+16 [J, animal products] + 6.26E+14 [J, fish] = **9.22E+16 J**. Solar transformity calculated from this study (note c).

Agricultural crops = 4.42E+09 [kg] (Statistics Sweden, 1997b, 1997c) x 3.85E+03 [kcal/kg] x 4.19E+03 [J/kcal] = 7.13E+16 J

Animal products = (5.48E+08 [kg, meat from husbandry farms] + 1.90E+06 [kg, reindeer meat] + 1.59E+07 [kg, wild game] + 7.14E+07 [kg, egg] + 3.26E+09 [kg, milk]) (Statistics Sweden, 1997b) = 3.89E+09 [kg, meat, milk and eggs] x 0.22 [% protein, given as decimal] x 2.37E+07 [J/kg protein] = 2.03E+16 J

Fish from fish farms, inland waters and sea = 1.25E+08 [kg, fish] (Statistics Sweden, 1998c, 1997a, 1998d) x 5.02E+06 [J/kg] = 6.26E+14 J

J_{Ex} Food export = 1.55E+16 [J, energy in cereal]+ 2.79E+14 [J, energy in meat] + 1.08E+15 [J, energy in fish] = **1.69E+16 J.** Solar transformity calculated from this study (item e).

Cereal exported = 9.65E+08 [kg] (Statistics Sweden, 1999) x 3.85E+03 [kcal/kg] x 4.19E+03 [J/kcal] = 1.55E+16 J

Meat export = 5.35E+07 [kg, meat] (Statistics Sweden, 1999) x 0.22 [% protein given as decimal] x 2.37E+07 [J/kg protein] = 2.79E+14 J

Fish export = 2.14E+08 [kg, fish] (Statistics Sweden, 1999) x 5.02E+06 [J/kg] = 1.08E+15 J

J_{Im} Food import = items 16+17+18+19

16. Meat import = 5.27E+07 [kg, meat] (Statistics Sweden, 1999) x 0.22 [% protein given as decimal] x 2.37E+07 [J/kg protein] = **2.76E+14 J**. Solar transformity from Ulgiati, et al (1993).
17. Fish import = 1.16E+08 [kg, fish] (Statistics Sweden, 1999) x 5.02E+06 [J/kg] = **5.84E+14 J**. Solar transformity from Hammer (1991).

18. Sugar import = 8.35E+06 [kg, sugar] (Statistics Sweden, 1999) x 1.70E+07 [J/kg] = **1.42E+14 J**. Solar transformity from Ulgiati, et al (1993).
19. Others imports of grain products, vegetables, fruit and nuts, coffee, tea, dairy products and eggs = 1.90E+09 [kg] (Statistics Sweden, 1999) x 3.85E+03 [kcal/kg] x 4.19E+03 [J/kcal] = **3.06E+16 J**. Solar transformity from Brown & Arding (1991).
20. Fuel used in processing = 2 [TWh, transportation] x 3.60E+15 [J/TWh, diesel] = **7.20E+15 J**. (Transportation used in processing and distribution sectors, 5 TWh/yr; Uhlin (1997) estimates 40% used in processing and 60% in distribution. Solar transformity from Lagerberg, et al (1999).
21. Electricity used in processing = 2.43E+06 [MWh] (Stat. Sweden, 1999) x 3.60E+09 [J/MWh] = **8.73E+15 J**. Solar transformity from Lagerberg, et al (1999).
22. Machinery use and inventory in processing = 3.06E+09 [SEK] (Statistics Sweden, 1999) x 6.70 [SEK/USD, 1996 exchange rate] = **4.57E+08 USD.** Multiplier = solar emergy per GDP (note a).
23. Building construction and maintenance in processing = 8.03E+08 [SEK] (Statistics Sweden, 1999) x 6.70 [SEK/USD, 1996 exchange rate] = **1.20E+08 USD.** Multiplier = solar emergy/GDP (note a).
24. Labour hours in processing = **6.09E+07** [hrs] (Statistics Sweden, 1999). Multiplier = solar emergy per hour (note b).
25. Expenditures for purchased resources used in processing = 1.67E+11 [SEK, cost of consumed food] (Statistics Sweden, 1997b) x 0.26* [% of cost, given as a decimal] / 6.70 [SEK/USD, 1996 exchange rate] = **6.48E+09 USD**. Multiplier = solar emergy per GDP (note a).

J_2 Processed food products = 4.42E+16 [J, grain and other crop products] + 1.27E+16 [J, meat and dairy products] + 7.95E+14 [J, fish products] + 2.48E+16 [J, other food products] = 8.26E+16 J (Statistics Sweden, 1997b, 1998b). Solar transformity calculated from this study (item d).

26. Fuel used in distribution = 3 [TWh, transportation] x 3.60E+15 [J/TWh] = **1.08E+16 J** (see note 20). Solar transformity from Lagerberg, et al (1999).
27. Electricity used in distribution = 3.70E+00 [TWh] (Statistics Sweden, 1999) x 3.60E+15 [J/TWh] = **1.33E+16 J**. Solar transformity from Lagerberg, et al (1999).
28. Machinery use and inventory in distribution = 1.49E+09 [SEK] (Statistics Sweden, 1999) x 6.70 [SEK/USD, 1996 exchange rate] = **2.22E+08 USD.** Multiplier = solar emergy per GDP (note a).
29. Building construction and maintenance in distribution = 6.56E+08 [SEK] (Statistics Sweden, 1999) x 6.70 [SEK/USD, 1996 exchange rate] = **9.79E+07 USD.** Multiplier = solar emergy per GDP (note a).
30. Labour hours in distribution = 6.76E+04 [people working] (Statistics Sweden, 1999) x 30 [average working hours per person per week] x 49 [work weeks per person per year] = **9.94E+07 hrs** Multiplier = solar emergy per hour (note b).
31. Expenditures for purchased resources used in distribution = 1.67E+11 [SEK, cost of consumed food] (Statistics Sweden, 1997b) x 0.58* [% of costs, given as decimal] / 6.70 [SEK/USD, 1996 exchange rate] = **1.45E+10 USD**. Multiplier = solar emergy per GDP (note a).

J_3 Food products bought at markets = 4.30E+16 [J, grain and other crop products] + 1.23E+16 [J, meat and dairy products] + 7.72E+14 [J, fish] + 7.72E+14 [J, other food products] = **8.02E+16 J**. Solar transformity calculated from this study (item e).

Grain and other crop products = 2.67E+09 [kg] (Statistics Sweden. 1997b) x 3.85E+03 [kcal/kg] x 4.19E+03 [J/kcal] = 4.30E+16 J

Meat and dairy products = 2.35E+09 [kg] (Statistics Sweden, 1997b; Statistics Sweden, 1998b x 0.22 [% protein given as decimal] x 2.37E+07 [J/kg protein] = 1.23E+16 J

Fish products = 1.54E+08 [kg] (Statistics Sweden, 1997b) x 5.02E+06 [J/kg] = 7.72E+14 J

Other food products = 1.50E+09 [kg] (Statistics Sweden, 1997b) x 3.85E+03 [kcal/kg] x 4.19E+03 [J/kcal] = 2.41E+16 J

32. Fuel used by consumers for food related transports = **9.80E+15 J.** Solar transformity from Lagerberg, et al (1999). petrol = 2.64E+05 [m^3] (Uhlin, 1997) x 1000 [l/m^3] x 3.56E+07 [J/l] = 9.40E+15 J; diesel = 1.12E+04 [m^3] (Uhlin, 1997) x 1000 [l/m^3] x 3.56E+07 [J/l] = 3.97E+14 J.

33. Electricity used in households for storage, cooking and washing = 7.18 [TWh, electricity] (Uhlin, 1997) x 3.60E+15 [J/TWh] = **2.58E+16 J**. Solar transformity from Lagerberg, et al (1999).

34. Expenditures for purchased resources used in food consumption = 3.24E+8 [USD, cost for fuel] 6.86E+08 [USD, cost for electricity] = **1.01E+09 USD.** Multiplier = solar emergy per GDP (note a).

Fuel use by consumers = 2 .75E+08 [l, petrol] (Uhlin, 1997) x 7 .89 [SEK/l, mean price for petrol 1996] (OK Q8, personal communication) x 6.70 [SEK/USD, 1996 exchange rate] = 3.24E+08 USD

Electricity use by consumers = 7 .18 [TWh, electricity] x 1E+09 [kWh/TWh] x 0.64 [SEK/kWh, price for electricity] (Uppsala Energi AB, personal communication) x 6.70 [SEK/USD, 1996 exchange rate] = 6.86E+08 USD

J_4 Consumed food products = 8.02E+16 [J, note35] (Statistics Sweden, 1997b, 1998b) x 0.88 (12% lost in the household as waste) = **7.05E+16 J**

Appendix B