Environmental Imprint of Human Food Consumption

Linköping, Sweden 1870–2000

Tina-Simone Schmid Neset
to my family
Abstract

Human food consumption has changed from the late 19th century to the turn of the millennium, and so has the need for resources to sustain this consumption. For the city of Linköping, situated in southeastern Sweden, the environmental imprint of an average inhabitant’s food consumption is studied from the year 1870 to the year 2000. The average consumer is the driving factor in this study, since changes in food consumption have a direct influence on the environmental imprint. This thesis analyses the environmental imprint of human food consumption from a historical perspective, by applying two different methods. An analysis of the average Swedish food consumption creates the basis for a material flow analysis of nitrogen and phosphorus, as well as a study of the spatial imprint.

Emissions of nitrogen and phosphorus into the hydrosphere have decreased over this period for the system of food consumption and production for an average consumer, while the input via chemical fertilizer has increased significantly. The efficiency of this system could be increased if for instance more phosphorus in human excreta would be reused within the system instead of large deposition and losses into the hydrosphere. The spatial imprint of human food consumption shows, given the changing local preconditions, that less space would be needed for regional production of the consumed food. However, the share of today’s import and thus globally produced food doubles this spatial imprint.

The results of this study show not only a strong influence of the consumption of meat and other animal products on the environmental imprint, but also great potential in the regional production of food. In the context of an increasing urban population, and thus additional billions of people who will live at an increasing distance from the agricultural production land, concern for the direct effects of our human food consumption can be of decisive importance for future sustainable food supply.

Keywords: food consumption, 19th and 20th century, Sweden, material flow analysis (MFA), substance flow analysis, nitrogen, phosphorus, spatial imprint
This thesis is based on the following papers, which will be referred to in the text by their Roman numerals:


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INTRODUCTION

From the very first moment of existence, a human being demands nourishment in order to sustain its need for energy, proteins and minerals to live and grow. This nourishment is initially obtained from the nearby surroundings. However, in order to sustain our diet, we utilize the soil and other natural resources from the environment. Whether or not these resources are used in a sustainable manner depends on many different factors, not at least on the individual diet and the population level. The basic need for nourishment seems however to be exceeded by increasing consumption and availability of food. In the case of a northern European country like Sweden, late 19th century industrialization gave way to a general rising food consumption\(^1\) leading to a population that increased in height, but also in average body mass. Quantitative proof of this is, for instance, the increase in the average weight and height of young Swedish soldiers\(^2\). Furthermore, the number of overweight people has significantly increased over the past decades in Sweden, and obesity is being considered a national health problem (Rössner 2002; SCB 2005b). This development is reflected in our demand on the environment as our pantry.

The production of food has changed significantly since the late 19th century and the demand for more and cheaper products has moved the production area from nearby fields to distant continents. Agriculture has become increasingly resource-intensive in terms of the use of both (fossil) energy and fertilizer, while the composition of the human diet has developed towards more animal products, the production of which demands more space and resources to produce. The consumer is considered the driving factor in this study, since changes in the average diet can influence the entire system of food consumption and production and thus the environmental imprint. In particular the increase in urban population might be a factor that induces more resource-intensive food consumption.

The point of departure is to investigate some of the regional and global impacts on the environment, in respect to area and resources that are caused by human

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\(^1\) Especially a higher intake of energy, with higher fat rate per energy unit.

\(^2\) Tänneryd (1998) and Pliktverket (2005) supplied information on young Swedish soldiers, where the average height increased from 167.4 cm in 1841 to 179.9 cm in 2000; Average weight increased from 65.8 kg in 1962 to 73.6 kg in 2000. From 1980 to the year 2000, the average weight of Swedish men and women increased by around 4 kg, while the average height increased by about 2 cm (SCB 2005a).
food consumption, combined with the shifting agricultural food production over the period from the late 19th century until the turn of the millennium.

The aim of this study is to quantify and analyze some specific aspects of the environmental imprint of human food consumption, based on the example of an average inhabitant of the city of Linköping, situated in the county of Östergötland in southeastern Sweden, from the year 1870 to the year 2000. In order to evaluate the impact of the average food consumption (Paper I) on the environment, I chose to study the flow of nitrogen (Paper II) and phosphorus (Paper III and IV), as well as the spatial imprint (Paper V).

The main research questions are:

1) What historical changes can be detected in the environmental imprint of human food consumption from the year 1870 to the year 2000?

2) How does the flow of nitrogen and phosphorus change during this period? How do changes in consumption, agricultural production and waste handling influence the use and reuse of these nutrients?

3) How does the area that is needed to sustain the consumption of a local population change? What potential lies in regional development and self-supply, compared to more globalized food production?

In order to study the environmental imprint of human food consumption, different viewpoints have been used. To compile data on the average consumption of food from 1870 to 2000, a large number of dietary regulations for various hospitals all over Sweden, as well as literature and statistics concerning this subject, have been studied in Paper I. The results of this paper will be introduced in chapter 4. Based on Paper I, the flow of nitrogen and phosphorus is studied, in Paper II and III respectively, for the consumption and production of food, which corresponds to the functional subsystem “activity to nourish” (Baccini and Brunner 1991; Baccini and Bader 1996; Brunner and Rechberger 2004). Paper IV focuses on the process of waste handling, during the same time period, for the flow of phosphorus and its potential reuse with different sanitary arrangements. The results of Paper II, III and IV will be introduced and discussed in chapter 5. Material flow analysis, which is the method used in Paper II to IV is introduced in chapter 2. Paper V calculates the spatial imprint of food consumption for an inhabitant of Linköping for 1870, 1900, 1950 and 2000, which is methodologically linked to the concept of the ecological footprint (Wackernagel and Rees 1996). All calculations in Paper II to V are based on an average consumer, an inhabitant of Linköping, and on the regional agricultural production in the county of Östergötland, for the period 1870 to 2000.
CHAPTER 2

METHODS

Food and environment

The English economist and demographer Thomas Robert Malthus, argued as early as in the late 18th century his theory that human kind, only through strict limitations on reproduction, would be able to sustain its supply of food (Malthus 2001; Linnér 2003). In the period after the Second World War, the Swedish-American scientist Georg Borgström debated the sustainability of food reserves. His approach to human food consumption was expressed in his concept of ghost acreages. The term describes what in the modern ecological footprint-literature is referred to as the “overshoot” (Wackernagel et al 2002) of land that for instance a nation needs in order to sustain its food consumption. As Linnér (1998:194-195) states in his thesis *The World Household*, “Borgström anticipated the concept ecological footprints” with the ghost acreages. The concern for the sustainability of human food consumption, has been discussed by many other authors during recent years. The World Watch Institute has, in a number of articles, stated this apprehension (e.g. Brown 1999) and several other studies consider the impact of human food consumption on the environment (e.g. Meadows et al 1972; Harris and Kennedy 1999; Linnér 2003). The United Nations predict a population increase in urban areas of over two billion people from 2000 to 2030 (UN Statistics database; medium variant). Thus, in 2030, 61% of the global population is expected to be living in urban areas, with most certainly a significant distance to the agricultural land where their food is produced. Moreover, the *Living Planet Report 2002* (WWF 2002) predicts an increase in global meat and fish consumption from 2000 to 2050 of 100%, which will probably lead to a significantly greater need for resources, such as nutrients and space for production.

A common question in this context is whether or not it is possible to sustain the future human food consumption, especially considering a possible shift towards a consumption pattern with increasing amounts of meat and other animal products on a global scale. Attempts at carrying out a quantitative study of human food consumption’s need for resources have been made from different angles, of which two are applied in this study. These are material flow analysis

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ii Which was first published in 1798.

iv This term was defined by Borgström as ”the computed, non-visible acreage, which a country would require as a supplement to its present visible agricultural acreage in the form of tiled land in order to be able to feed itself” (cited from Linnér 1998:194).
and the spatial imprint. Both have a rather similar agenda – to shed light on the human impact on the environment in a quantitative context.

This thesis focuses on the historical changes in the environmental imprint of human food consumption by applying two separate methods of quantification. A significant factor in this study is the relatively long time period of 130 years and the rather small scale of the study area, which makes it possible to study a per capita model and to include specific regional preconditions. This study reconstructs the agricultural area in the region, based on local individual consumption. Accordingly, the actual growth of the city area is not taken into account, but the number of inhabitants and the changes that are relevant to the analysis of this study, such as the sanitary system.

The questions posed in this study demand different methods of quantification in order to provide a more specific knowledge about the relationship between human food consumption and the environment. The flow of nutrients is studied with a material flow analysis and leans towards the concept of activities in order to determine a functional subsystem for this study. The methodological approach of the spatial imprint is closely related to the concept of the ecological footprint. Three resources were chosen to quantify this impact;

1) The flow of nitrogen through the system of food consumption and production
2) The flow of phosphorus through the system of food consumption and production, with a specific analysis of phosphorus reuse in waste handling
3) The area needed to sustain an average per capita consumption

The common basis for this study is the endeavor to analyze the environmental impact, not by a mere measurement of pollutants, but by focusing on the average consumer’s impact on the entire cycle of production and consumption. Thus, it makes it possible to follow the effect of minor changes as well as shifting conditions, as for instance in agricultural practices and techniques. The spatial imprint and material flow analysis provide a more precise understanding of human activities, such as utilization of common resources. They do not single out specific processes or products, but visualize the complete system of, for example, the entire area needed for an individual’s food consumption. In a quantitative manner, they relate human activities and the assessed use of resources to the impact that these have on the environment. Both methods expand on the problem of human food consumption and the use of resources and relate this to consumers and their interaction with the environment. Furthermore, the following subjects will be targeted by applying these two methods: Firstly, the changing diet, predominantly the increase in the consumption of meat and other animal products, has to be taken into account.
in the context of an increasing urban population; Secondly the self-sufficiency of regions versus the increasing distance between the production area and the consumer, and whether the latter must be considered a threat to a secured global food supply.

Studies that often focus on similar questions are for instance studies of nutrient budgets based on recipients or catchment area (e.g. Karlsson 1989; Stålnacke 1996; Arheimer et al 1997; Naturvårdsverket 1997a; Obernosterer et al 1998; Somloyódy et al 1999; Laakonen and Lehtonen 1999; Savage 2003), as well as agricultural system analysis (Andersson 1986; Naturvårdsverket 1997b; Hoffinan 1999) that both have a long tradition. Quantitative analyses of human consumption and its impact on the environment have also been considered in for instance Life Cycle Analysis and Energy Flow Studies, which analyze certain products or compile the use of a resource for a certain amount of food (e.g. Andersson 1998; Carlsson-Kanyama and Faist 2000; Cederberg 2002; Engström 2004). However, the two methods that are applied in this study were chosen due to their capability of considering a larger context systematically and thus analyzing the interrelationship of human food consumption and the environment in a complex framework of human activities (cf Baccini and Brunner 1991).

Material Flow Analysis

Material flow analysis is a method used to describe in a systematic way the correlation of different processes and the flows between them. It is a common tool used to analyze the flows in the human sphere - the anthroposphere (Baccini and Brunner 1991), based on the principle of mass balance (input equals output or results in a change in the stock). A material flow system consists of a system border, processes, and the flow of goods, materials or substances, between these processes, as well as flows into and out of the system.

Starting in the 1970s (e.g. Newcombe et al 1978; Rauhut 1979), the metabolism of cities and regions has been studied in a quantitative manner regarding the flow of materials and/or substances affected by human activities. The terminology “industrial metabolism” was introduced in the 1980s by Robert U Ayres (Lohm 1998; Brunner and Rechberger 2004). Subsequently, the concept of the metabolism of society, often referred to as “industry”, was further developed and applied in several research projects and publications (e.g. Baccini and Brunner 1991; Ayres and Simonis 1994; Brunner et al 1994; Fischer-Kowalski 1998; Ayres 1999; Ayres and Ayres 2002). A functional approach to the anthroposphere is the division into four different activities as defined in Baccini and Brunner (1991), Baccini and Bader (1996) and Brunner and Rechberger
These activities aim to include all flows of the anthroposphere and hence cover all human related flows. They are: to nourish, to live and work, to transport and communicate and to clean. This study has an approach that is similar to the functional subsystem activity to nourish, in order to capture main processes that are related to human food consumption.

The common terminology in the field of industrial ecology distinguishes between material and substance flow analysis. Substance flow analysis refers to single substances, as for instance heavy metals or biocides with a more or less specific environmental impact, while material flow analysis refers to studies of larger materials or products, signified by larger masses or volumes, such as water, oil or timber (Lohm 1998). In this study, the method itself has been labeled as material flow analysis whether it refers to either material or substance flows. Specific to this study is the methodological stretch towards a historical material flow analysis. The historical material flow analysis demands a broad approach for the collection of data and information, since specific measurements are rarely available. In order to make the historical input data computable, the data relating to product groups, production and consumption variables and other information have to be categorized and unified. Furthermore, the historical perspective puts demands on the model and especially the dynamic modeling, since only some points in time could be quantified.

Other studies have, in a similar way to this study, analyzed the environmental impact of food production and consumption, and focused on the flow of nutrients and/or energy. Van der Voet (1996) studied the nitrogen flows of the European Union, with specific focus on the agricultural sector. Here the major conclusions were that the main flows of nitrogen derived from food production and that a strong reduction would only be possible with either a shift in diet or a radical change in agricultural policies and practices. Bleken and Bakken (1997) analyzed the nitrogen cost of food production for Norway. They stated that changes towards a more vegetarian diet as well as a better utilization of food could lead to major reductions in the Norwegian consumption of nitrogen. Pfister (2003) has studied a material flow analysis system for a rural Nicaraguan region. The results show evidence of nitrogen mining in the agricultural system, primarily in the soil for the production of staples, coffee and forest, and the need for new strategies in farm management. Faist (2000) analyzed the resource efficiency of the “activity to nourish”, considering primary energy, focusing on different stakeholders’ decision making. However, energy saving measures that would be economically attractive could not be identified, since no significant decrease could be achieved using the studied measures along with low energy costs in the single processes. Kytzia et al (2004) studied the food production chain with an economically extended material flow analysis, and found that a vegan diet had a great influence on both energy consumption and land use in
their case study, situated in the Swiss lowlands. The interrelationship of different Swiss regions was analyzed in Hug (2002) regarding energy flows and the “activity to nourish”, and a low level of self-sufficiency of both the alpine and the lowland region was stated.

For this study two different material flow analysis systems were defined. These will be hereafter referred to as system I and system II. System I is the main system, defined by the flows of nitrogen and phosphorus in food consumption and production. System II is “zooming in” on the process of waste handling, focusing on the reuse of phosphorus.

**Modeling procedure**

The method used here is the well known standard modeling concept. The procedure consists of the following four steps: 1) system analysis, 2) formulation of the model equations, 3) calibration and 4) simulation including sensitivity and uncertainty analysis as well as parameter variation. The system analysis is presented in detail in appendices A and B. The other steps will be discussed below.

**Mathematical model**


The dynamic model relates the time-dependent variables to each other by dynamic system equations. They describe mathematically the system behavior and the phenomenological knowledge of the system respectively. Mathematically,

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v System analysis is described as the definition of the system and its level of approximation; a) to define the boundary of the system considered and b) to define the processes and the flows between the processes taking the environment into account (definition by Bader and Scheidegger 2004).
the dynamic of the system is “hidden” in the structure and the type of equations and the so-called parameter functions.

System I, which is applied for the calculation of the flows of nitrogen and phosphorus for food consumption and production, is presented in appendix A. The overall system of 81 equations contains 83 parameter functions describing the 81 system variables. A further parameter function, representing the population of Linköping, is introduced in order to obtain results for the whole city and per capita respectively. Mathematically the equations are a set of 6 ordinary differential equations of first order, coupled with 75 algebraic equations. The initial conditions for the variables are defined by the flow pattern of figure 5.1 (see chapter 5). For system II, phosphorus flows in waste handling (chapter 5), the model approach uses 18 parameter functions to describe the system properties found, namely 2 input functions (consumption of vegetable and animal food) and 16 transfer-coefficients, describing the 5 “distribution” processes. All equations are given in appendix B. Figure 5.6 (see chapter 5) shows the flow pattern for this system, which defines the initial conditions for the variables. To distinguish system I for nitrogen (N) and phosphorus (P) from system II (waste handling), the notation Pw is used for the parameter functions of system II. Similar as for system I, the parameter functions are adapted to the available data in the calibration procedure described below (see also appendix A). The equations have been implemented in the computer program SIMBOX (Bader and Scheidegger 1995). All simulations, including uncertainty analysis have been performed on a Pentium 4/Celeron PC.

**Calibration**

Calibration is the art of finding both the appropriate parameter functions and the procedure to fit them to the available data. In general, the better the system knowledge, the more accurately the parameter functions are known.

The parameter functions for the system of nitrogen and phosphorus flows in food consumption and production (system I) can be roughly classified into the following 5 groups:

a) Consumption behavior:
Yearly amount of consumption of animal and vegetable products per capita.

b) Waste distribution patterns:
Transfercoefficients of waste from the processes waste, household and food processing to reuse as fodder, reuse as (human) fertilizer, or waste deposition and emissions to the atmosphere and hydrosphere.
c) Agricultural demand:
Specific amount of manure and fertilizer as well as specific area needed to grow vegetable and fodder.

d) Process efficiencies:
Ratio of processed to consumed food and ratio of produced and processed food.

e) Emission and leakage characteristic of agriculture:
Specific emissions and specific leakage from plant production to atmosphere and hydrosphere.

Group a) describes the consumption habit as a function of time, whereas groups b) – e) represent the time-dependent technical manipulations and the natural conditions of the system considered.

In this study, data are scarce: for the parameter functions of system I the data set provides a value for the years 1870, 1900, 1950 and 2000 with considerable uncertainty, especially in the distant past. Based on these rare data points, it was not possible to identify specific functional patterns for the different quantities. Therefore, in the sense of a first approximation, simple curvefits to the data have been chosen as parameter functions. The experience of experts in the field of curvefitting shows that interpolation with polynoms of low order is normally most suitable (Gnauck and Luther 2004). For that reason linear, quadratic (with minimal total curvature) and cubic splines (with zero curvature at both ends) were used as parameter functions. Figure A\textsubscript{1} in appendix A shows all 3 approximations. Finally, the most appropriate approximation has been selected, according to the intensity of oscillations and the plausibility of the results respectively. A problem commonly known using linear interpolation is the “roughness” of the fit originating from the discontinuity of the first derivative. This “roughness” can be reduced by smoothing the corresponding variables.

For system II, the procedure is similar to that used for system I. The parameter functions can be classified into two groups:

a) Consumption behavior: Input functions, containing the yearly amount of consumption of vegetable and animal food
b) Distribution patterns: Transfercoefficients of the five internal processes.

For the same reasons as in system I above, simple spline curvefits of first, second and third order have been chosen as parameter functions.
Error propagation and sensitivity analysis

Since the parameters most often include a specific uncertainty range, these uncertainties are subsequently conveyed to the variables (and stocks). Hedbrant and Sörme (2000) discuss the problem of uncertainties in material flow analysis for the case of urban heavy metal data collection. The historical data mainly supplied a minimum and maximum value for e.g. a certain yield per hectare, and thus, calculations were based on a mean value, while the range was taken into account in the uncertainty calculations. Further information can be obtained from appendices C and D. There are two different types of uncertainty calculations: First order calculations and calculations of the probability distribution of the variables\textsuperscript{vi}. Furthermore, sensitivity analysis can be applied to evaluate the influence of single parameters on the flows and stocks of the system. In Paper II, III and IV, the uncertainty was calculated for single parameters with the help of SIMBOX (Bader and Scheidegger 1995). For further information see chapter 5 and appendix C.

Spatial Imprint

The concept of the spatial imprint is applied in order to distinguish it from the method of the ecological footprint, which is presented below. As the imprint metaphor indicates, it is used to point out the specific need of space for a human activity. Furthermore, it enables a transparent calculation of the local area needed to sustain an average food consumption, and thus make the imprint historically comparable. The spatial imprint does not therefore consider area equivalents for other resources than space, as for instance energy, fertilizers and waste disposal.

The method of the ecological footprint has been created and developed by Wackernagel and Rees (1996) and has been used manifold in studies on the footprint of cities, regions and nations as well as international comparisons (e.g. Hakanen 1999; Lewan 2002; Sustainable Sonoma County with Redefining Progress 2002; Wackernagel et al 2002; WWF 2004, Johansson 2005). The ecological footprint is a spatial equivalent of biologically productive land as well as surface waters for all consumption. Most of the recent studies also include the need for energy and area for CO$_2$ assimilation and waste deposition (e.g. Wackernagel et al 2002; WWF 2004). For the calculation of the ecological footprint, the area for biomass production is estimated as a so-called global hectare. For this, the total global yield is divided by the total bioproductive area

\textsuperscript{vi} Based on the probability distribution of parameters using Monte Carlo simulations (definition by Bader and Scheidegger 2004).
and, in some cases, multiplied by an equivalence factor for the product in question. The global yield therefore provides a tool for international comparisons of the sum of an average individual’s influence on the global resource household and makes it possible to evaluate the impact of the lifestyles of various cities, regions or nations. The concept of the ecological footprint has been used in many different studies to illustrate the human use of resources. The Living Planet Report (WWF 2002; 2004) compiles the footprint of a large number of countries, from the smallest total footprint in 2001, of Afghanistan with 0.3 hectares per capita, up to the largest in 2001, of the USA with 9.5 hectares per capita. The area hereof that can be related to the production and consumption of food (sum of cropland, grazing land and fishing ground) would be 0.09 and 1.63 hectares per capita for Afghanistan and the USA respectively. The studies of Wackernagel et al (2002) and others that compare the ecological footprint of several nations and regions, show similar large variations (see Paper V).

The following studies cover the ecological footprint of food consumption and production from a historical perspective from the 19th century onwards. Land use changes in Austrian villages, situated in different parts of the country during the 19th century, were studied by Krausmann (2004). The investigation was based on the Franciscan Cadastre, and showed for 1830 an average food footprint of about 1.7 hectares per capita in the Austrian Upland, over 3 hectares per capita in the Alpine region and merely 0.77 hectares per capita in the Lowland. Cussó et al (2003) estimated for the Vallès County in Catalonia, Spain for 1860/1870 a requirement of 1.17 hectares to sustain an individual’s consumption, though including 0.48 hectares of forest. The Catalanian data was also based on cadastral sources. Although these historical studies are rather hard to compare due to differences in historical sources, definitions and analysis, the studies correspond rather well to each other, given their geographical location. Other studies have been conducted with a historical approach, though with a shorter time scale, by for instance Haberl et al (2001), Erb (2004) and Wackernagel et al (2004b). Krausmann (2004) and Cussó et al (2003) use the local yield in their studies. Erb (2004) studied the actual land area that was needed to sustain the consumption of Austria from 1926 to 2000, and Wackernagel et al (2004b) compared the actual land area approach to the conventional ecological footprint approach for Austria, the Philippines, and South Korea for the period 1961-1999. Specific conceptual problems with the method of the ecological footprint, such as the application of the local or global yield, were addressed in methodological discussions by several studies (Haberl et al 2001; Erb 2004; Monfreda et al 2004; Wackernagel et al 2004a).
Data uncertainties

The empirical data was obtained from various sources, both from archives, annual reports, literature and national statistics. Historical data unquestionably holds a certain amount of uncertainty, not at least for the late 20\textsuperscript{th} and early 21\textsuperscript{st} century, that have to be taken into account when modeling and calculating. Data used to define processes, transfer coefficients and flows inherit therefore a range of uncertainty, which has to be considered in the general conclusions by testing the sensitivity of the system.

In material flow analysis studies, the uncertainty or range of input data for single parameters is handled by testing the sensitivity of the system for the specific parameter or for several parameters. The flows in system I and II are tested for uncertainty in the input of food and the uncertainty in the fodder data and secondary waste and sludge handling data respectively. The results of the uncertainty analysis are presented in appendix C.

In the study of the spatial imprint (Paper V), the uncertainty or range of single input data was included in a straightforward manner into the calculations and resulted in a specific range, marked as “minimum” and “maximum”. Since the results show the sum of the total spatial imprint, the specific influence of a single parameter (i.e. beef production), is not visible. In ecological footprint studies, the uncertainties are caused by the input data and specifically by the following two approaches to the calculation of the footprint. The global yield, which is utilized in many studies, is based on a rough estimation of the total bioproducitive area that is used for the production of a certain food, divided by the total global yield of this food. Hence, global yield includes all production areas of the world and consequently uncertainties in data sources and information. The local yield, on the other hand, avoids this by using mostly national or regional data, which allows greater certainty in the factual data on the yield of certain foods. However, the local yield is often applied in historical studies, which in turn implies estimations for longer time periods and historical agricultural data with higher uncertainty. In Paper V, uncertainties in the local historical data are approached by including ranges for yield data of each food group, which in the end add up to a “minimum” and “maximum” result for each point in time.
Linköping

The setting of this study is the city of Linköping, situated in southeastern Sweden, in the county of Östergötland (cf figure 3.1). The appearance of the city has changed during the 130 years of this study from the clerical and administrative center of the county with about 7,300 inhabitants and has become the fifth largest municipality in Sweden with a major university, aircraft manufacturing and high-tech industry. In 2000 the inner city\textsuperscript{vii} had about 94,000 inhabitants (Linköpings kommun 2003). The surrounding countryside is characterized by a predominantly plane landscape with several larger lakes and rivers.

Figure 3.1
The city of Linköping in 1877 (Source: Lantmäteriet i Östergötlands län), situated in the county of Östergötland (in gray shading) in the South East of Sweden (Source: own).

\textsuperscript{vii} In Swedish: \textit{tätort}
The river Stångå which originates in the southern part of the county crosses through the city and is still to the present day, even though to some reduced share, both supplying the city with freshwater and receiving its wastewaters, before it flows into lake Roxen north of the city.

The county is situated in the boreonemoral vegetation zone, which is mainly defined by mixed forests, both coniferous trees and birch, but also oak, aspen and other deciduous trees, with a growing season of about 190-200 days (Raab and Vedin 1995). The average temperature ranges from –3/0 degrees Celsius in January to 15/17 degrees Celsius in July, and annual precipitation is on average 500-700 mm (Linköpings kommun 2003; average range for 1931 to 2000). The inland ice withdrew about 10 000 years ago. Due to the subsequent rise in sea level in the Baltic Sea, the county was covered with water, to which the fertile soils in the western part bear witness. The first settlements in this region were not established until 7000-6000 years BC (Söderbäck 1995; Engberg et al 1996). The terrain consists mainly of moraine and lime rich soils, often clay, with many lakes (Söderbäck 1995; Länsstyrelsen i Östergötlands län 1983). The second largest Swedish lake (Lake Vättern) defines the county border to the west and the Baltic Sea with its archipelago to the east.

The city and its waste handling system

In 1870 the city looked much like any other smaller city in Sweden at this time. Houses were mainly built of wood, except for a few larger stone buildings, that were situated around the market square. Small lots of urban agriculture could be found in the central parts of the city, where domestic animals were kept and urban gardening was practiced (cf figure 3.2).

The main implementation concerning infrastructure was the gas network that was installed in 1861 (Almroth and Kolsgård 1978) and demanded a large amount of the city’s financial resources. In 1872, Linköping was connected to the national railway (Noreen 1978). Apart from that, infrastructure was rudimentary. Streets were only partly covered with cobblestone. Water was fetched from the river Stångå, either directly or from pumps, or obtained from ground water wells with pumps in the center of the town. Human excreta were predominantly collected in cesspits and partly in more or less watertight buckets (Hallström 2002).
During the 1870s, the first water and wastewater system was constructed. Water was extracted upstream from the city from the river Stångå and transported with water-powered pumps to the reservoir that was situated just above the town on a hillside. From there, water ran with self-pressure through pipes to the yards and houses of the inner city. Sewer pipes were constructed in five dividing trails via the main streets down to the river Stångå. While sanitation still consisted mainly of cesspits and buckets, the following years introduced both urine-diverting toilets and the first water closets (Hallström 2002). Concurrently, the sewer system successively expanded (cf figure 3.3). During this early period, latrines were collected from yards and mainly distributed to the nearby arable land, whereas some share of 10-30% was expected to be fed to livestock such as pigs that were kept in the city. During the following decades, a rising number of houses and apartments were connected to the water and sewer system, and the number of water closets increased.
By the 1950s, when the first wastewater treatment plant was built, about 90% of all inhabitants were connected to the urban sewers, and about 60% of these were linked to the wastewater treatment plant. However, early mechanical treatment did not remove a large proportion of the nutrients that were contained in the urban sewerage. The nutrient-poor sludge was mainly deposited. Not until the 1970s was a special purification of phosphorus introduced (see appendix D). Sludge dehydration facilitated the reuse of the nutrients in agriculture and increasing amounts were subsequently recycled, until a sludge boycott was initiated by the farmers union (LRF) in the late 1980s and 1990s (Agustinsson).

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\(^{viii}\) In order to reduce inconsistency in the database, the year 1950 applies data for the sanitary system of the year 1952, when the wastewater treatment plant was installed.
Nationwide, in 2000, on average 21% of the sludge produced was reused in Swedish agriculture (Naturvårdsverket 2002).x

**Historical development in the regional agriculture**

Linköping is surrounded by a plane and fertile agricultural landscape with production of primarily cereal crops, but also vegetables and fruits, as well as livestock breeding, dairy and egg production. Agricultural productivity of these products has increased significantly over the period of 130 years, due to advances in agricultural practices and techniques, increased use of (fossil) energy and chemical fertilizers, but also due to crop improvement and animal breeding.x

Data for 1870 and 1900 was mainly compiled from the Agricultural Society of the County of Östergötland (Östergötlands läns hushållningssällskap, HÖ), however information on some products or for some years, which were incomplete for the county, had to be obtained from national Swedish historical data.

For 1950, the average yield for Östergötland was received from the national Swedish historical statistics (SOS 1959), while for the year 2000, official statistics were available on a county basis (SCB 2001; SCB and SJV 2003).

Figure 3.4 shows the average yield for compiled and generalized food groups. While cereals, fruits and sugar increased in a rather linear manner, the yield per hectare for vegetables and potatoes increased considerably from 1950 to 2000.

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xi In Linköping the variations in data on sludge reuse concerning the years around 2000 are great (Tekniska Verken 1991-2002). Thus, the Swedish average was used in this study since it was considered most representative. In the case of Linköping, a large share of this agricultural area is not used for food production, but for energy forest, which is not specified in system II, but will be discussed in Paper IV.

xIn Swedish: förädling and avel
Agricultural yield per hectare and year in the county of Östergötland (data for sugar and fruits are based on Swedish average data due to lack of information for the county of Östergötland) based on HÖ (1869-1951); SOS (1959); SCB (2001); SCB and SJV (2003).

The vast increase in yield was, as mentioned above, partly based on the increased use of chemical fertilizer. Animal manure was at all times used in agriculture, and a thorough analysis of the historical development of the use of manure and fertilizer in Sweden during the late 19th and early 20th century (Hoffman 1999) supplied information on the use of nitrogen in both manure and chemical fertilizer. The proportion of phosphorus in manure had to be assumed to be equivalent during the entire period, due to a lack of more concise data on this matter. Phosphorus in chemical fertilizer was calculated according to Jansson (1988). For the year 2000, the use of nitrogen and phosphorus via fertilizer was supplied by the official agricultural statistics (SOS 2003a). The average application of nitrogen and phosphorus through manure has approximately doubled from 1870 to 2000, and the application of chemical fertilizer to arable land rose from none in 1870 to a high application in the year 2000 of 7 kg of phosphorus per hectare per year and to over 60 kg of nitrogen per hectare per year (see appendix D). Information on emissions from agriculture for 1870, 1900

Note, that only data points for the 4 points in time exist. Hence, the linear development between these points in time is merely an assumption. For 1870 and 1900 data for vegetables was, due to lack of more precise data, calculated on an average of legumes, peas and root crops, and for fruits data was calculated on an average for apples, pears and plums. For 1950 and 2000 all data was calculated in relation to the average consumption. (For further information see appendix D).
and partly for 1950 was obtained from Hoffman (1999). Additional information was obtained from national agricultural statistics (SOS 2003a).

Figure 3.5
Livestock on pasture on the outskirts of the town; Valla, 1903
Today this area is close to the University Campus.
(Source: Didrik von Essen 1903, Östergötlands Länsmuseum)

Regarding the information on animal production (cf figure 3.5), the historical data is less specific. A larger statistical investigation has been conducted by the Agricultural Society of the County of Östergötland on the production of milk, with an overview from 1900 to 1950 (HÖ 1951). The input of fodder for the production of one liter of milk decreased from about 2.7 kg in 1870 to about 1.5 kg in 1950. For the year 2000, the calculations carried out by the Swedish Environmental Protection Agency (Naturvårdsverket 1997e) were used, giving an input of on average 0.8 kg per liter of milk. The composition of fodder changed significantly however over time. Considering the production of meat, data was calculated based on an annual report of the county’s agricultural school (HÖ 1885) and a similar advance in breeding as in dairy farming was assumed. An average for the 1950s for meat, egg and poultry production was given by Norin (1963). For 2000, information was mainly obtained from two complementary sources (SLU 1996; Naturvårdsverket 1997e). For further information see appendix D.
FOOD AND CONSUMPTION CHANGES

Food consumption has a significant impact on the use of resources such as space, water, energy and nutrients. Paper I studies the quantity and composition of the Swedish diet based on hospital dietary regulations from 1871 to 1928 (Royal Medical Archives). The consumption of 1930-1940 is obtained from reports on living standards from official statistics (Kungliga Socialstyrelsen 1938; 1943), and a national average calculated by the economist Lars Juréen (cited in Morell 1989). From 1950 to 2000, official national statistics were used, giving an annual per capita consumption (SJV 2003a).

Figure 4.1 shows the relative distribution of food, divided into three groups, for the study period. The proportion of meat and fish increased from 11 to 16 %, while dairy products and egg decreased (note that dairy products are calculated in kg of food, not milk equivalents). The proportion of vegetable products increased from 37 to 54% despite a decrease in the consumption of cereals.
Paper I shows a distinctive increase in the consumption of meat, fish, vegetables and fruits. The consumption of cereals and milk, on the other hand, decreased over the same period. Furthermore, a clear regional pattern in the consumption of meat and fish in the dietary regulations could be noted.

The results were compared to several national investigations and studies of German and Finnish food consumption in the late 19th and early 20th century. Particular attention had to be paid to those foods which were exaggerated in the hospital diet due to special nutritious value or nutrient-cost efficiency, such as milk, cereals and meat. Uncertainties in the hospital diet have been evaluated and a national study has been used for the average data of meat, milk and cheese in the following studies (Paper II to V). However, clear trends can be stated for the general development of human food consumption for an average Swedish consumer. Most distinctive is the increase in meat consumption. The average consumer has during this period almost doubled their consumption of meat, which is an important factor in the following estimation of the environmental imprint of human food consumption. Figure 4.2 shows the increase in consumption of meat and fish during this period.

Figure 4.2
The daily per capita consumption of meat and fish (1871 to 1928 is based on the hospital diet studied in Paper I). Average value in kg.

Another important change is the decrease in consumption of milk, but increase in the total consumption of dairy products, when considering the amount of milk required for the production of cheese and butter. The consumption of
cereals has decreased, while the amount of potatoes consumed has more than doubled from 1900 to 1950 (see Paper I).

Despite the fact that the hospital diet represents an institutional diet, and hence has for instance possibilities for storage, the chosen group of patients in the main ward\textsuperscript{xii} appeared to be fairly comparable to the average of the Swedish population. Even if this meant ill or convalescent people “in a state of rest”, the average of patients of all ages, both male and female, was very much coherent with other studies of the average national diet, both for Sweden and comparable countries (cf Paper I). For the following studies (Paper II, III, IV and V), however, three food groups that were strongly influenced by the character of the hospital diet – meat, milk and cheese, were applied according to data obtained from the 1942 investigation of the average Swedish diet, based on import, export and production statistics by Juréen (cited in Morell, 1989), as described in appendix D.

Figure 4.3
Women sorting peas at Linköping’s canning factory around 1950
(Source: Arne Gustafsson, Bild Linköping)

\textsuperscript{xii} In Swedish: \textit{allmän sal}
While food processing has mostly been a household-based activity in early times, the upcoming industrial processing of the 20th century (cf figure 4.3) created increasing amounts of organic waste that were only partially reused in animal or plant production (see appendix D). Concurrently, new freezing and conservation techniques made foods available for consumption at all times and thus probably contributed to dietary changes.

The increase in food consumption, both in terms of energy as well as most animal products, as shown in Paper I, is most certainly reflected in the increase in height and weight of the Swedish population. Tänneryd (1998) has compiled historical data on the height of young Swedish men being examined for military service, and stated an increase in height from 1.67 meters on average in 1841 to 1.79 meters in 1997. An increase in weight for young Swedish soldiers of 7.8 kg from 1962 to 2000 was noted by the Swedish National Service Administration (Pliktverket 2005).
CHAPTER 5

FOOD AND NUTRIENT FLOWS

The flow of nutrients for the system of food consumption and production is studied for nitrogen and phosphorus (Paper III and IV). Both nutrients are significant for the environmental imprint of changes in food consumption and production. The system for both nutrients is defined in the same way and describes flows into and within the system, but also emissions into the environment. The efficiency in usage of both nutrients is subject to the analysis.

System

The system border is defined by the consumption and production of food for an average inhabitant of Linköping for the years 1870, 1900, 1950 and 2000. In total the system consists of 81 equations linking the 81 variables. Figure 5.1 presents the 24 main flows for this system. Flows of products from animal and plant production to industrial processing, the flow of food from industrial to household processing as well as the flow of food from household processing to consumption are divided into several sub-flows, in order to facilitate specific calculations for each of the 11 food groups. The four years that were investigated (1870, 1900, 1950, 2000) for the flows of nitrogen and phosphorus were chosen as representative for the stages of development in food consumption, agriculture, but also the sanitary system of the city. These four “typologies” represent a shifting context that can be analyzed through the two nutrients nitrogen and phosphorus. Both have very specific characteristics that make them invaluable for the analysis of the system. The six processes that are included in this system are:

(1) Animal Production
(2) Plant Production
(3) Industrial Processing
(4) Household Processing
(5) Consumption
(6) Waste Handling
Nitrogen is most essential for sustaining organisms. It is part of most organic matter and appears in amino acids, nucleic acids, enzymes and chlorophyll (Smil 1990). Furthermore, nitrogen in different chemical forms is found both in aquatic as well as atmospheric media, and has therefore a rather intricate cycle. Besides its role as a component of nitrous oxide, one of the most important greenhouse gases, which has one of its main anthropogenic sources from agriculture (IPCC 1996), it is also a key contributor to eutrophication of surface waters in the Swedish environment. Most nitrogen that is emitted into rivers, lakes and the Baltic Sea originates from agriculture, but the local wastewater treatment plants should not be underestimated either regarding point pollutions. Various nitrogen compounds which impact differently on the environment are part of the flows within this system. The Swedish Environmental Protection Agency aims for a decrease in nitrogen emissions to the hydrosphere (zero
eutrophication), which is still however an ongoing environmental challenge (Naturvårdsverket 1997a; Naturvårdsverket 1997f; Bratt 2003). In Paper II, the flow of nitrogen is analyzed for the system of food consumption and production.

Food and nitrogen flows

The total flow of nitrogen for the four years that were modeled (1870, 1900, 1950, 2000) is shown in figure 5.2 below. The flow of nitrogen is quantified as the total amount of input, internal flows and output flows. The impact on the environment from different nitrogen compounds is however not quantified, as for instance the proportion of N$_2$ and N$_2$O is not specified in this model (for further information see appendix D).

Figure 5.2 cf page 32
Figure 5.2 cf page 32
Figure 5.2

The required flow of nitrogen for human food consumption and production. Calculations are based on an average inhabitant of Linköping for the years 1870, 1900, 1950 and 2000, and a regional production of all food. The data gives the flow of nitrogen in kg per capita and year. Stocks are calculated, but due to the definition of the system they are not shown or discussed in this study.

Figure 5.2 shows the results of the flow of nitrogen through the system of food consumption and production, where the variation in the preconditions of each time-specific system is the basis for the shift in flows during this period.

Comparing the development for the entire period, the total load per capita disposed of into the environment decreased by about 30%. Emissions into the hydrosphere from waste handling increased from 0.57 kg to 3.1 kg N/cap per year. There was no flow of nitrogen to the waste deposit in 1870 and 1900, however in the year 2000 1.7 kg N/cap were deposited. The largest flow was fodder from plant production to animal production, which decreased from 23 kg N/cap per year to 18.5 kg N/cap per year, followed by chemical fertilizer, which rose from zero to 15 kg N/cap per year in 2000.
A different reflection of this development is the relationship between reuse and losses in the human-determined use and handling of nitrogen. The ratio of reused nitrogen, defined as the reuse flows from industrial and household processing as well as waste handling to animal and plant production, opposed to losses from these three processes, decreased considerably during this period. Figure 5.3 shows this ratio, reflecting a development from a high reuse level of close to 3:1 to a comparably nearly insignificant reuse level of about 1:3.

The generalized development for the ratio of the total sum of reused flows to the total sum of losses (from industrial and household processing as well as waste handling). Calculations are based on an average inhabitant of Linköping from 1870 to 2000. Note that only four data points were given (1870, 1900, 1950, 2000).

The balance of, for instance, the process plant production indicates evidence of nitrogen mining, especially in the early years. However, since nitrogen-saving practices such as fallow and crop sequence are not included in the calculations, the negative stocks that can be found in the system (predominantly in the process plant production) are not significant for the region or the agricultural soil itself, but merely for the per capita calculations, which are based on an average consumer in an abstract system.

The efficiency of plant production has increased significantly during this period, as has the efficiency of animal production. The ratio of nitrogen in fodder versus nitrogen in animal product (meat and dairy products) has decreased to a third of the original amount during this period, i.e. the efficiency of input fodder for the output animal product has increased threefold, from about 9:1 to about 3:1.
Phosphorus

Phosphorus is a limited resource, and of great interest for food security, as it is an essential nutrient for the agricultural production of food. At the same time it creates a pollution problem for the aquatic environment in Sweden, contributing to eutrophication of surface waters and the Baltic Sea. The recycling of phosphorus is therefore of great importance for a secured food supply and sustainable food production, both in a local and global perspective and to prevent pollution of the local environment (Runge-Metzger 1995; Naturvårdsverket 1997c; Naturvårdsverket 2002; Rosemarin 2004).

The expected cease of the global resources of mineable phosphorus rock is by some researchers estimated to occur as early as in 130 years (Smil 1990; Günther 1997, Rosemarin 2004), based on the current utilization in agriculture. Phosphorus can however be recycled from the urban sewerage and reused in agriculture (see Paper IV). Although this potential has long been known, the modern sewer system has developed in the opposite direction and increasingly lost the phosphorus directly to the hydrosphere or created a toxic and therefore valueless sludge from which phosphorus is hardly reusable. In this chapter, the flow of phosphorus through the system of food consumption and production from 1870 to 2000 will be presented. The chapter on phosphorus reuse in waste handling will then be focusing on the historical development and future possibilities of phosphorus recycling within waste handling.

Food and phosphorus flows

The changes in flows between the different processes of the system as well as input flows and output flows to the environment are shown in figure 5.4. The flow of phosphorus in food to the consumer (and in the same way the output to the process of waste handling) increased by about 30%. The output flow to the hydrosphere decreased by about 30%, while the output flow to the waste deposit increased from zero in 1870 to 0.55 kg/cap per year in 2000. The largest flows are those of fodder, which decreased from 3.4 and 3.9 kg/cap per year in 1870 and 1900 respectively to 3 kg/cap per year in 2000, and the flow of manure from animal production to plant production, which decreased from 2.5 kg/cap per year in 1870, after a peak in 1950, to 1.8 kg/cap per year in 2000. Overall, the flows within the system remained relatively stable, despite significant changes in agricultural efficiency and food consumption.

Figure 5.4 also shows an imbalance in the system and in some processes, stocks of phosphorus accumulate. The accumulation in the process animal production
is shown as surplus output flow from the system. The stock in the process of plant production is not shown in figure 5.4, since it is considered insignificant for the purpose of this study. Phosphorus has been “mined” from agricultural ground since more phosphorus was removed by harvest and leakage than contributed by natural or chemical fertilization. However, in our abstract per capita system, the lack of crop sequence, fallow, and other agricultural preconditions give an unfortunately inaccurate picture on this point. The result indicates phosphorus mining in 1870 and 1900, while for instance the practice of regular fallow partly prohibited such mining.

Figure 5.4 cf page 37
Figure 5.4 cf page 37
The required flow of phosphorus in 1870, 1900, 1950 and 2000 for the consumption and production of food for one average inhabitant of Linköping. The data gives the flow of phosphorus in kg per capita and year. Stocks are calculated, but due to the definition of the system not shown or discussed in this study, since they are insignificant in this specific analysis.

The phosphorus reuse ratio, calculated using the sum of reuse flows and the sum of losses from industrial and household processing, as well as waste handling to animal and plant production, indicates a significant decrease from 1870 to 2000. The generalized development is shown in figure 5.5. The initially high reuse of 8:1 decreased to a ratio of 1:1.5 with less reuse than losses. It has to be noted, that this graph is only based on data for four points in time. Intensive phosphorus purification since the 1970s, combined with the dehydration of sludge from the wastewater treatment plant made a higher reuse of phosphorus from human excreta possible (see Paper IV).
The generalized development for the ratio of the total sum of reused flows to the total sum of losses (from industrial and household processing as well as waste handling). Calculations are based on an average inhabitant of Linköping for the years 1870 to 2000. Note that only four data points were given (1870, 1900, 1950, 2000).

The main reason for this development is the vast shift in waste handling, which was the largest contributing factor in this decrease. The figures for the average Swedish reuse of sludge in agriculture partly obscure the fact that a certain proportion of this sludge is used for energy forest and not for food production. Due to the ongoing sludge boycott, initiated by the Swedish Farmers Union, the reuse of sludge, and thus phosphorus from human excreta, on arable land might possibly even decrease further in the near future. For a scarce resource such as phosphorus, this development is most certainly alarming. Therefore, Paper IV, which will be presented in the subsequent chapter, focuses on the process of waste handling. Even though the largest flows are to and from the process plant production, alternatives in sanitation arrangements have great potential for resource conservation, as will be shown in the following.

**Phosphorus recycling in waste handling**

Paper IV studies phosphorus recycling, focusing on the practical and possible reuse of phosphorus with regard to different sanitary arrangements. The system identifies the main processes and flows included in the historical, modern and alternative waste handling of human excreta.

The phosphorus flow model for waste handling is constructed as follows; the system border is defined by waste handling of human excreta. It consists of five processes within the system;
(1) human consumption
(2) faeces collection
(3) urine collection
(4) secondary treatment
(5) sludge handling

and five processes outside the system border;

(6) livestock
(7) plants, soil
(8) energy system/energy forest
(9) hydrosphere
(10) landfill

Figure 5.6
The system of consumption and waste handling for the flow of phosphorus per capita and year (system II). The boxes indicate processes and the arrows indicate the related input and output flows with a description of the flow. The system border is defined for the food consumption and waste handling for an average inhabitant of Linköping.

The procedure is rather similar to the nitrogen and phosphorus household of system I. Therefore only the most important steps are discussed in appendix B. Paper IV analyses the generalized development of the reuse of nutrients from human excreta for the city of Linköping, which can be considered the approximate development for most Swedish cities. During these 130 years, the system has gone through some noticeable changes.
In 1870, a considerable proportion of the phosphorus in urine and faeces was recycled. During the following years, most faeces were still collected in cesspits, however some urine diversion was introduced and urine was led into the newly built sewer pipes that lead in the river Stångå, the local recipient. In 1900, some water closets had been installed, and more phosphorus that was contained in both urine and faeces was directly discharged into the river. All cesspits had by then been replaced by watertight buckets (Hallström 2002). Due to the increasing number of water closets in the city and a further expansion of the sewer pipe network, the reuse of phosphorus from human excreta diminished drastically during the following decennia. When in the 1950s the majority of inhabitants were connected to the newly built wastewater treatment plant, only a small proportion of the phosphorus from sewer sludge was extracted, and due to the lack of dehydration, the extracted phosphorus ended up on the landfill. In the early 1970s the wastewater treatment plant was equipped with a phosphorus purification unit, and about 90% of the phosphorus was extracted from the incoming wastewater. Sludge dehydration facilitated the reuse of phosphorus-rich sludge in agriculture. In 2000, phosphorus removal in the wastewater treatment plant was about 97%, but due to resistance to the application of phosphorus-rich sludge in agriculture, the majority was deposited on the landfill. The system in figure 5.7 shows for the beginning and the end of our observation period the specific flow of phosphorus from human consumption through the waste handling system (for further results see Paper IV). It is necessary to bear in mind, though, that this calculation only considers approximately less than two thirds in 1870 and about one fifth in 2000 of the total turnover of phosphorus in the system of food production.

Turnover in this case is based on the total input to the processes plant production and animal production (see Paper III). In 1870, this is 0.74 of which 0.43 kg per capita per year is the proportion that is released to the waste handling system. In 2000, the amounts are 2.48 kg per capita per year, of which 0.57 is released from the process human consumption.
A significant factor in this system is the total reuse of phosphorus over time in livestock breeding and agriculture. The main development is described by the sum of all reuse as shown in figure 5.8. Since system II, in contrast to system I,
includes several additional points in time, the graph shows the changes in reuse caused by a) the total connection to the sewers up to the 1950s, b) the additional phosphorus purification unit in 1972, which facilitated an extraction of 90% of the phosphorus from the incoming wastewater, and c) the shift in sludge reuse.

![Graph showing changes in reuse](image)

Figure 5.8

Sum of all reuse from the system of waste handling in total amounts of phosphorus in kg per capita per year from 1870 to 2000.

Calculations show a rather distinct development; the shift in sanitation arrangements, which can be described as from recycling to linear, has contributed to a reduced reuse of phosphorus. Linköping can be considered a typical example for the Swedish, or even European path from small local sanitation arrangements, with reuse from latrines to the soil, to large-scale, technical solutions. Western society has built its way into a sanitation system during the last centuries, which destined the path to a linear flow of nutrients (Drangert and Hallström 2002; Hallström 2002; Drangert and Löwgren 2005; Drangert and Hallström 2005). However, since the deposition of organic waste on landfills has been prohibited since the beginning of 2005 (Olofsson 2004), new paths have to be tested. The Swedish Environmental Protection Agency aims as a first step for reuse of at least 60% of the phosphorus in sewerage on productive soil, and at least half of this on arable soil, by 2015 (Naturvårdsverket 2002:68). However, a shift to a reuse system (i.e. ecological sanitation), which most certainly would be of great advantage in reducing the environmental imprint, needs to meet the standards of users. These users might have become reluctant to exchange their perceived simple, hygienic and convenient system, since the comfort they are familiar with might be compromised (Krantz 2005). However, great potential lies in improvements of the sanitary arrangements, not least considering the overall importance of reusing the nutrient resources from human excreta for the global food supply.
Discussion

The reuse ratio for both nitrogen and phosphorus per capita evolved from a high to a low reuse. In the case of nitrogen, losses from the system of food consumption and production into the environment decreased by about 30%. Emissions of phosphorus into the environment increased significantly from 1870 to 1950, but decreased again towards 2000 to a lower level than in 1870, due to the implemented phosphorus purification at the wastewater treatment plant. Most of the recovered phosphorus, however, ended up on the deposit and has therefore not been reused. Efficiency within agricultural production had a strong impact on both the flow of nitrogen and phosphorus, as did a distinctively higher input of chemical fertilizer within plant production. The influence of a greater or lesser amount of meat and other animal products in the diet is of particular interest. The largest flow in both systems is that of fodder to the process animal production. Hence, the consumption of meat has a strong impact on the total sum of all flows. Given the increased efficiency of input fodder and output animal product, a diet with approximately half the amount of meat and dairy products (in milk equivalents), as for instance the average diet in 1870, which was used for this calculation, would result in a reduced need for chemical fertilizer by 15% for nitrogen and 25% for phosphorus respectively. Output flows to the hydrosphere would in this scenario diminish by 20-24%.

A shift in fertilizer usage, given the scenario of a total reuse of human excreta, could theoretically sustain 27% of the total phosphorus and up to one third of the total nitrogen in fertilizer required for food production. For a diet with a lower intake of meat, such as that described above, an even larger amount of the fertilizer needed could be sustained by such a reuse. Ecological sanitation (e.g. Jönsson et al 2004; Drangert 2004) shows a path for securing nutrients from human excreta and to sustain a secure and efficient supply of essential components for food production.

The question of how valid the conclusions are, regarding the uncertainties in the empirical data remains. The sensitivity matrix has been calculated for nitrogen and phosphorus for system I and for phosphorus in system II. In system I, the parameters fodder (linked to variable $A_{21}$, appendix A) and food (linked to variable $A_{35}$, appendix A) are the two parameters with the greatest impact, and

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xiv The diet for 1870 includes obviously more changes than the reduced consumption of meat and dairy products. However, the area needed for fodder production is substantially larger than the remaining area in plant production. Thus, large changes in fruits and vegetables would, especially considering the high agricultural efficiency of the regional agriculture in the year 2000, only lead to marginal changes.
were thus chosen for uncertainty calculations. The results for selected variables are presented in appendix C.

For system I, three cases were defined and uncertainties were calculated based on the uncertainty for the input data of food and fodder for 1870, 1900, 1950 and 2000, as defined in appendix C. Case 1 and 2 calculated the uncertainty for the input of food and the input of fodder separately. The results show the influence of these uncertainties on other variables within the system. As could be expected, it shows a greater uncertainty in 1870 and 1900, compared with 1950 and 2000, except for those flows that were relatively small in the early period, as for instance chemical fertilizer. Case 3 calculated the uncertainty for a combination of cases 1 and 2, thus adding together the uncertainties of both cases. Despite a higher uncertainty in 1870 and 1900, the total development of most flows was only to some degree compromised. The largest uncertainty range was around ±30% for the selected variables. For the output flow to the hydrosphere, the flow of neither nitrogen nor phosphorus changed notably in Case 3. The input of chemical fertilizer, which is an important variable to the system, was not influenced either in its development. The general conclusion of this sensitivity study is that there is a relatively high degree of certainty in our analysis of the historical development of food consumption and production.

For system II, uncertainty calculations for two cases were conducted, as described in the appendix. The variables sum of all reuse, losses to hydrosphere and sum of all losses were the variables that were chosen as examples, since they together indicate the sum of all output flows from the system. Case 1, which was formulated similarly as in system I, calculated the uncertainty for the input of prepared food for the selected variables. For this case, only the magnitude of the flows changed. The assessed range for the input data for secondary waste treatment and sludge handling was used for comparison of results for the same three variables in Case 2. The largest uncertainty range in the results was in the period 1970 to 2000, caused by the uncertainty in sludge handling. Despite large variations in the input data, the variable losses to the hydrosphere was not influenced to a high degree by these uncertainties.
A specific amount of space is needed in order to sustain an individual’s food consumption. Some important factors that determine the extent of this area are the quantity and composition of the diet as well as the preconditions and practices of the agricultural production. The historical comparison of the spatial imprint of human food consumption shows a distinct variation over time. One contributing factor is the increasing yield per hectare due to changing agricultural techniques and geographical circumstances. Furthermore, the area can be linked to the use of other resources such as water, energy and fertilizer and related environmental impacts such as pollution and land degradation.

Spatial imprint of food consumption and production

In Paper V, the changing spatial imprint of an average inhabitant of the city of Linköping is studied and covers calculations for the years 1870, 1900, 1950 and 2000. A changing human consumption (cf chapter 4) and advances in agricultural practices are the main contributors to these changes. This study reconstructed the agricultural area in the region that would be needed to produce an individual’s food consumption.

The equations below describe the calculations of the spatial imprint (SI). SI \(_{(a)}\) refers to the calculations for 1870, 1900, 1950 and 2000\( (a)\), and shows hence an exclusively regional production of all food. Calculations are based on the annual consumption per capita for the different foods \((C)\), losses in household processing \((H)\), industrial processing \((P)\), and harvest spill \((S)\) divided by the local yield \((LY)\) factor.

SI \(_{(a)}\) refers to the calculation of 2000\( (b)\). This scenario includes the imported proportion of all foods, based on the proportion of local production \((L)\) and import \((I)\) respectively. All imported foods are assumed to be produced with a global yield \((GY)\), which is obtained from Wackernagel et al (spreadsheet).

\[
SI_{(a)} = \frac{(C_{1870} + H_{1870} + P_{1870} + S_{1870})}{LY_{1870}}
\]

\[
SI_{(b)} = L \times \frac{(C_{2000} + H_{2000} + P_{2000} + S_{2000})}{LY_{2000}} + I \times \frac{C_{2000}}{GY_{2000}}
\]
The amount of space needed to sustain the annual food consumption of an average inhabitant of Linköping decreased significantly from the year 1870 to the year 2000 (figure 6.1). A regional production of all food products would require on average about one quarter of the area in the year 2000(a) compared to 1870, despite a larger amount of consumed meat in the year 2000.

Figure 6.1
Minimum and maximum area needed to sustain an individual's annual consumption based on an exclusive regional production; 1870, 1900, 1950, 2000(a) and on a “global production” that includes the share of the imported foods for 2000(b). The black line indicates the mean value. The range is based on uncertainties derived from individual consumption, waste losses in household and industry, agriculture, animal feed and agricultural yield.

Including imported foods, and assuming a production of these imported foods on a global scale, using the global footprint according to Wackernagel et al (2002; spreadsheet) the calculations for 2000(b) lead to a distinctively larger spatial imprint. The proportion of animal products in the diet has a particularly strong impact on the spatial imprint. Looking in particular at the increase from 2000(a) to 2000(b), i.e. the increased area needed when a certain amount of food is imported and hence produced on a global yield, animal products account for the majority of this escalation (figure 6.2). However, also historically, animal products demand most of the area for food production, with on average 80 to 85% of the total spatial imprint.
Figure 6.2
Share of vegetable and animal products to the total spatial imprint based on the average value.

If these results are put into the context of the growing city and an increasing number of urban inhabitants, that need to be fed by their hinterland, the number of hectares needed to produce this supply changes considerably as shown in figure 6.3. For the city of Linköping, the increase in inhabitants in the inner city from 7,300 in the year 1870 to 94,000 in the year 2000, is shown clearly in the total spatial imprint of the city (figure 6.3). The area needed to sustain the total food consumption increased over this period, with a peak in 1950. Including the global area for the production of imported foods, the area in 2000(b) is about six times as large as in 1870. In comparison, the actual area of agricultural land in the county of Östergötland was close to 260,000 hectares in 2000 (arable land including pasture), with a total number of inhabitants of 411,000, and thus, the available agricultural land was about 0.6 hectares per capita (SCB and SJV 2003). In Sweden as a whole, the amount of arable land decreased from 3.4 million hectares in the late nineteenth century (Morell 2001) to 2.7 million hectares in 2000 (SCB and SJV 2003).
Figure 6.3 also shows the vast influence of animal products. For the city of Linköping 90% of the total spatial imprint in 2000(b) is caused by animal products, while with a regional production of all foods, this proportion would diminish to 82%. However, the results in figure 6.2 and 6.3 clearly show that changes in the consumption of animal products would have the greatest effect for the reduction of the total spatial imprint of human food consumption, both for the average individual consumer as well as for the sum of all inhabitants of Linköping.

Discussion

In general this study of the spatial imprint showed that the increased efficiency in food production presents the possibility of a much smaller spatial imprint per capita if the food is produced within the region. This is in spite of the increase in consumption of more area (and resource) intensive foods. However, given the global production area of imported foods in 2000, the probable per capita spatial imprint of an average consumer in Linköping is about twice as large as it would be with a regional food production. Considering the increase in population, the spatial imprint has increased manifold during the 130 years of
this study, as shown in figure 6.3. The great potential of a more or less vegetarian diet to reduce the environmental imprint can be exemplified by a simple calculation. Given the assumption that no meat or fish is consumed, and is instead replaced by equal proportions of vegetable and dairy products (see appendix D), a simple approximation indicates that the spatial imprint per capita of an average individual food consumption could be reduced by about 50%. Similarly, if the average inhabitant of Linköping would have changed their diet in 2000 to that of 1870 (which means about half the meat and dairy consumption), an approximately 30% smaller area would be needed. Hence, a shift towards a diet with less animal products would result in a smaller spatial imprint.

The specific influence of the agricultural development can be exemplified in the following approximation. If the diet of 1950 would be produced under the agricultural conditions of the year 2000, the spatial imprint per capita would be 60% smaller if production was regional, but less than 20% smaller if production includes the global production area of imported foods. The strong effect of more regional production of food products is revealed in this hypothetical scenario. As is shown above, a regional production of all food products (2000(a)) would demand considerably less area than for a food production that is global for all imported foods (2000(b)), both for the average consumer (figure 6.2) as well as the entire city of Linköping (figure 6.3). This type of scenario would, of course, imply an endeavor on the part of the county of Östergötland to be self-sufficient, which would oppose the current ongoing decrease of arable land used for agriculture since the early 20th century. The spatial imprint thus shows the potential in regional development, and promotes further discussion.

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xv For the calculations, the average footprint with the conditions of 2000(a) was calculated according to the diet of 1870. The spatial imprint of this calculation was 34% smaller than the result of 2000(a). Including the global production of imported foods, the diet of 1870 would, given the conditions of 2000(b) lead to a 26% reduction. The influence of meat and dairy consumption on this imprint was one of the most significant contributors, but obviously other factors contributed to the outcome of this scenario.

xvi Compared to the spatial imprint of 1950.
CHAPTER 7

FOOD AND RESOURCES – GENERAL CONCLUSION

This thesis showed that the historical changes in human food consumption most certainly have a marked impact on the environment. How this impact is expressed differs depending on the substance, material, or resource that is studied, and results may vary depending on the definition of system border and specific research question. This study chose two methods and three different resources to answer the main question of what historical changes could be detected in the environmental imprint of human food consumption from the year 1870 to the year 2000.

The general results of this study lead to the following conclusions; Comparing the year 1870 to the year 2000, the diet of an average inhabitant of the city of Linköping demands less area today. If all food were produced regionally, a significantly smaller spatial imprint would be necessary, than in the case of a diet that contained large amounts of imported foods. The choice of food, in respect to animal or vegetable compounds, has a significant impact on the size of the spatial imprint. Furthermore, urbanization has led to an increasing distance between consumer and production area. The global production of food contributed with about 60% of the spatial imprint for the year 2000(b). Of particular interest is the effect of population increase in the city during this period. The total spatial imprint of food consumption of the inhabitants of Linköping in 1870 is merely one quarter to one fifth of the spatial imprint of 2000, and regional production would have an even more important effect.

The analysis of the flow of nutrients for the system of food consumption and production gave a similar result. Per capita, the emissions into the environment decreased for both nitrogen and phosphorus. Nitrogen leakage from plant production to the hydrosphere decreased by about 60% from 1870 to 2000, while the amount of nitrogen from sewerage to the aquatic recipient increased more than fivefold over the same period of time. For phosphorus, emissions into the environment increased towards the 1950s, but dropped thereafter up to the year 2000 to a level that was lower than at the beginning of the study in 1870. However, the output flow to the waste deposit increased from zero in 1870 to over half a kilo per capita per year in 2000, and for nitrogen from zero to 1.7 kg over the same period. Similarly, the input of phosphorus in chemical fertilizer increased from zero to 2 kg per capita in 2000, and nitrogen in chemical fertilizer from zero to 15 kg per capita in the year 2000. Including the population increase for this period, the output of phosphorus to the waste deposit increased from zero to nearly 52 ton and the input of phosphorus in
chemical fertilizer similarly from zero to 188 ton per year. The approximate numbers for the total flow of nitrogen to the waste deposit was an increase of nearly 160 ton per year and over 1400 ton of nitrogen in chemical fertilizer for Linköping. Correspondingly, the diminished reuse ratio has an even larger effect on the nitrogen and phosphorus cycle considering the population increase than for the average consumer. Even if the flow of nutrients from agriculture is significantly larger than the output from the wastewater treatment plant, when considering the big picture of for instance an entire river basin (Karlsson 1989), a fairly large proportion of up to 27% of the phosphorus and up to 35% of the nitrogen (cf chapter 5) needed in chemical fertilizer could be replaced by reuse of human excreta. The flows of nitrogen and phosphorus show moreover a geographical dimension - in the shape of food and chemical fertilizer they are often transported from distant regions, before passing consumption and finally ending up in local Swedish watersheds and modern sewers, and contribute correspondingly to nutrient mining and leakage in production areas in other countries and on other continents.

What significance has the increase in consumption of meat and other animal products, for the environmental imprint of human food consumption? The results of the spatial imprint study (Paper V) indicated that a diet with less meat and dairy products (such as the diet of 1870) demands about 30% less area, given the same conditions. Also, the amount of phosphorus in chemical fertilizer needed for food production would be reduced by 25%, and for nitrogen in chemical fertilizer by 15%. Moreover, distinctively less emissions into the hydrosphere can be expected. These results are confirmed by several other studies (e.g. Piementel and Houser 1997; Sustainable Sonoma County with Redefining Progress 2002; Pfister 2003).

Once more it has to be pointed out that the main reason for the diminished need, per capita, of space and emissions to the environment is the increase in agricultural productivity, which is facilitated by advances in agricultural practice and technique, animal breeding and crop improvement; and which is most important for this discussion, though, by the increased input of chemical fertilizer and fossil energy. The two latter resources represent the decreased sustainability of food production and should be considered most significant in this context.

What conclusions can be made concerning the environmental imprint of human food consumption, comparing two different methods of analysis which reflect the changes in space and the flow of nutrients? An unambiguous and legible result is the development of the spatial imprint (Paper V). It showed clearly, how the composition of human consumption and the development in agricultural technique and practices changed the total amount of space that is needed to
sustain an average consumption. Thus, it reflects for instance the proportion of animal and vegetable products to this area. Compared to material flow analysis, assumptions and the influence of single processes to the total sum are not transparent in the final result. Material flow analysis on the other hand, is a method that provides more detailed results, and thus could be a basis for detailed policy discussions. The three material flow systems that are provided in this study (Paper II, III and IV) are rather complex. Nevertheless, for the purpose of answering the main questions that were posed, some results can be singled out, explicitly some specific flows and the reuse ratio for all substance reuse in each system. The material flow analysis studies in Paper II, III and IV, show only single flows and their order of magnitude for the total emissions. They do however indicate the distinct impact of changed conditions on single flows, such as emissions into the hydrosphere or the input of fertilizer, as well as the reuse ratio (for processing, consumption and waste handling) for each nutrient.

All of these studies (Paper II to V) show, that the food consumption of an average inhabitant of Linköping would be possible to sustain with a smaller environmental imprint than in 2000. The use of area for the production of food, which in its turn influences the flow of nutrients, could diminish significantly. Subsequently, the emission of nutrients into the environment as well as the input of nutrients from outside the system (i.e. chemical fertilizer) and losses to waste deposits could be diminished. The high share of imported foods, that is consumed in the region, as well as decreasing reuse of nitrogen and phosphorus within the system of food production and consumption, result, however, in a less sustainable and more resource-demanding consumption today, than would be necessary. This is not only true for the individual average consumer, but most certainly for the city of Linköping and its increasing population.

From a global perspective, urbanization plays an significant role, both a) considering its effect on a shifting lifestyle and shifting consumption – mainly in terms of distance between consumer and agriculture, but presumably even for the proportion of animal products - and b) in respect to its effect on losses and reuse of nutrient resources by the development and future potential of the sanitation system. Urbanization possesses great potential for environmentally sustainable technical solutions (such as waste recycling, collection, energy saving measures, alternative energy sources etc), although industrialized countries have mostly chosen a path of technical end-of-pipe solutions. However, expanding cities on all continents, which have not yet chosen a similar path of linear nutrient flows have significantly greater potential for adapting to ecological sanitation arrangements with relatively simple technical solutions. A closer (production-consumption-waste reuse) cycle between the city and its hinterland would not only lead to resource conservation but would also most certainly increase the environmental consciousness of consumers. Subsequently, it could
lead to consumption choices that are, according to the conclusions of this study, necessary for the future sustainability of food consumption and production. One such example could be a regional self-supply of food, and consequent potential for regional development that could be the result of a diet without imported foods. This would also imply a regional nutrient conservation.

To conclude, it can be stated that the system of food consumption and production has changed considerably during the 130 years of this study. Many different factors have influenced this system. The average human consumption, which drives this system, has shifted its composition towards more meat and other animal products. Furthermore an increasing proportion of consumed food is produced further and further away from the consumer. Agricultural practices have been intensified through technical advances such as crop improvement, chemical fertilizer, and the use of fossil fuels, which all resulted in a rising yield per hectare. The waste handling system has changed during this period from a system of reuse of most of the human excreta and organic residues towards a predominantly linear flow of substances out of the system, aiming for hydrosphere or waste deposit.

The predictions for the system of one average consumer will be even more accentuated by the predicted increase in – particularly urban – population. The urban lifestyle in particular has, during recent decades, led the food production area further away from the consumer. Both this and the global development that, to some degree suggests a parallel increase of the consumption of meat and other animal products, need to be further investigated. Such a scenario enforces the sustainability of global food consumption as a critical issue, since the production of animal products demands more area and resources, as is claimed by this thesis and other studies with comparable results. Consequently, both a decrease in meat consumption, and other animal products, as well as a development towards local production of food is essential for sustainable human food consumption. What remains to be done is the further development of scenarios, particularly concerning the potential of food consumption and choices consumers are able to make, and their impact on environmental sustainability. In the end, it will probably take a new generation of consumers to change the general perception that food and most other resources can be taken for granted.
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Appendix A: System I

1. System variables

The following variables describe the system shown in figure 5.1 completely:

Stocks:
- $M^{(1)}$: Stock in animal production
- $M^{(2)}$: Stock in vegetable production
- $M^{(3)}$: Stock in household
- $M^{(4)}$: Stock in food processing
- $M^{(5)}$: Consumer stock
- $M^{(6)}$: Stock in waste processing

Flows:

The flows are listed according to the process they belong to, starting from waste processing.

Waste processing:
- $A_{56}$: Excreta
- $O_1$: Emission of waste to hydrosphere
- $O_2$: Emission of waste to atmosphere
- $O_3$: Waste deposit
- $A_{62}$: Human fertilizer (Night soil)
- $A_{61}$: Latrines

Consumer:
- $A_{35}^{(1)}$: Beef consumption
- $A_{35}^{(2)}$: Pork consumption
- $A_{35}^{(3)}$: Poultry consumption
- $A_{35}^{(4)}$: Fish consumption
- $A_{35}^{(5)}$: Milk and dairy consumption
- $A_{35}^{(6)}$: Egg consumption
- $A_{35}^{(7)}$: Potato consumption
- $A_{35}^{(8)}$: Cereal consumption
- $A_{35}^{(9)}$: Vegetable consumption
- $A_{35}^{(10)}$: Fruit consumption
- $A_{35}^{(11)}$: Sugar consumption
Household processing:

\[ O_4 \] : Organic waste from household
\[ A_{31} \] : Organic waste as fodder from household
\[ A_{32} \] : Organic waste as fertilizer from household
\[ A_{43}^{(1)} \] : Beef to household
\[ A_{43}^{(2)} \] : Pork to household
\[ A_{43}^{(3)} \] : Poultry to household
\[ A_{43}^{(4)} \] : Fish to household
\[ A_{43}^{(5)} \] : Milk and dairy to household
\[ A_{43}^{(6)} \] : Egg to household
\[ A_{43}^{(7)} \] : Potato to household
\[ A_{43}^{(8)} \] : Cereal to household
\[ A_{43}^{(9)} \] : Vegetable to household
\[ A_{43}^{(10)} \] : Fruit to household
\[ A_{43}^{(11)} \] : Sugar to household

Industrial processing:

\[ O_5 \] : Organic waste from processing
\[ A_{41} \] : Organic waste as fodder from processing
\[ A_{42} \] : Organic waste as fertilizer from processing
\[ A_{44}^{(1)} \] : Beef to processing
\[ A_{44}^{(2)} \] : Pork to processing
\[ A_{44}^{(3)} \] : Poultry to processing
\[ A_{44}^{(4)} \] : Fish to processing
\[ A_{44}^{(5)} \] : Milk and dairy to processing
\[ A_{44}^{(6)} \] : Egg to processing
\[ A_{24}^{(1)} \] : Potato to processing
\[ A_{24}^{(2)} \] : Cereal to processing
\[ A_{24}^{(3)} \] : Vegetable to processing
\[ A_{24}^{(4)} \] : Fruit to processing
\[ A_{24}^{(5)} \] : Sugar to processing

Vegetable production:

\[ A_{12} \] : Manure
\[ A_{21} \] : Fodder
\[ I_1 \] : Fixation and deposition
\[ I_2 \] : Chemical fertilizer
\[ O_6 \] : Emission from agriculture
\[ O_7 \] : Leakage from agriculture
Animal production:

\(O_8\) : Surplus manure
\(O_9\) : Emission from animal production

Auxiliary variables:

\(H_1\) : Area for animal production
\(H_2\) : Area for vegetable production
\(H_3\) : Total area of food production
\(H_4\) : Sum of meat consumption
\(H_5\) : Sum of vegetable consumption
\(H_6\) : Sum of total consumption
\(H_7\) : Sum of meat production
\(H_8\) : Sum of vegetable production
\(H_9\) : Sum of all reuse flows
\(H_{10}\) : Sum of all losses
\(H_{11}\) : Ratio of all reuse/all losses
\(H_{12}\) : Ratio of all losses/all reuse
\(H_{13}\) : Sum of reuse flows waste
\(H_{14}\) : Sum of losses of waste
\(H_{15}\) : Ratio of waste reuse/waste losses
\(H_{16}\) : Ratio of waste losses/waste reuse

Including also the stock change rates \(\dot{M}^{(i)}, \ldots, \dot{M}^{(6)}\) these are 81 time-dependent variables in total.

2. Model equations

The extended study to quantify the regional food consumption, described in chapter 5, allowed to gain insight into the system behavior. This system knowledge suggests a “consumer driven” approach where the input flows to the consumption process are fitted to historical data. All other flows are related to these “key-flows” as will be shown below. Thereby the relations represent the technical and natural conditions in function of time.

\(i)\) intrinsic equations between \(M^{(i)}\) and \(\dot{M}^{(i)}\):

\[
M^{(i)}(t) = M^{(i)}(0) + \int_0^t \dot{M}^{(i)}(t') dt' \quad \quad \quad i=1,\ldots,6 \quad (3)
\]
ii) Balance equations:

\[ \dot{M}^{(1)}(t) = A_{41} + A_{21} + A_{31} + A_{61} - A_{12} - \sum_{j=1}^{6} A_{41}^{(j)} - O_8 - O_9 \quad (4a) \]

\[ \dot{M}^{(2)}(t) = A_{12} + A_{42} + A_{32} + A_{62} + I_1 + I_2 - A_{21} - \sum_{j=1}^{5} A_{42}^{(j)} - O_6 - O_7 \quad (4b) \]

\[ \dot{M}^{(3)}(t) = \sum_{j=1}^{11} A_{43}^{(j)} - A_{31} - A_{32} - \sum_{j=1}^{11} A_{35}^{(j)} \quad (4c) \]

\[ \dot{M}^{(4)}(t) = \sum_{j=1}^{6} A_{44}^{(j)} + \sum_{j=1}^{3} A_{42}^{(j)} - A_{41} - A_{42} - \sum_{j=1}^{11} A_{43}^{(j)} - O_5 \quad (4d) \]

\[ \dot{M}^{(5)}(t) = \sum_{j=1}^{11} A_{35}^{(j)} - A_{56} \quad (4e) \]

\[ \dot{M}^{(6)}(t) = A_{56} - A_{62} - A_{61} - O_1 - O_2 - O_3 \quad (4f) \]

iii) Model approach:

In the same way as for the variables, the equations are listed according to the process they belong to, starting from waste processing.

Note that the equations hold for both N and P, of course with corresponding parameter functions.

A. Waste processing:

Excreta related to food consumption

\[ A_{56}(t) = (1 - P_1^{(w)}(t)) \sum_{j=1}^{11} A_{35}^{(j)} \quad (5a) \]

\[ P_1^{(w)}(t) : \quad \text{Retention in body} \]

The superscript \( w \) indicates that the parameter function belongs to waste processing.

Emissions to hydrosphere, atmosphere, and waste deposit:

\[ O_1(t) = P_2^{(w)}(t) A_{56}(t) \quad (5b) \]

\[ O_2(t) = P_3^{(w)}(t) A_{56}(t) \quad (5c) \]

\[ O_3(t) = P_4^{(w)}(t) A_{56}(t) \quad (5d) \]

where:

\[ P_2^{(w)}(t) : \quad \text{Transfercoefficient of waste to spill of excreta} \]

\[ P_3^{(w)}(t) : \quad \text{Transfercoefficient of waste to waste emissions into atmosphere} \]

\[ P_4^{(w)}(t) : \quad \text{Transfercoefficient of waste to waste deposition} \]
Use of excreta as fodder:

\[ A_{61}(t) = P_5^{(w)}(t)(A_{36}(t) - O_1(t) - O_2(t) - O_3(t)) \]  

(5c)

where

\[ P_5^{(w)}(t) \quad \text{Transfer coefficient of waste to use of excreta as fodder} \]

No stock accumulation in waste processing:

\[ \dot{M}^{(b)}(t) = 0 \quad (5f) \]

The parameter functions \( P_1^{(w)}(t), \ldots, P_5^{(w)}(t) \) are the characteristics of the process waste handling, and represent the technical progress and the socio-economic habit of excreta usage and losses in function of time.

B. Consumer process:

Consumption of the various food:

\[ A_{35}^{(i)} = P_1^{(c)}(t) \quad (6a) \]

\[ P_1^{(c)}(t) : \quad \text{Beef consumption} \]

\[ \ldots \]

\[ A_{35}^{(i)} = P_1^{(c)}(t) \quad (6k) \]

\[ P_1^{(c)}(t) : \quad \text{Sugar consumption} \]

Similar to waste processing, the parameter functions \( P_1^{(c)}(t), \ldots, P_{11}^{(c)}(t) \) represent the consumption habits for the different food in function of time.

C. Process household:

\[ A_{43}^{(i)}(t) = P_1^{(b)}(t)A_{35}^{(i)}(t) \quad (7a) \]

\[ P_1^{(b)}(t) : \quad \text{Ratio of processed meat to consumed meat} \]

\[ \ldots \]

\[ A_{43}^{(i)}(t) = P_2^{(b)}(t)A_{35}^{(i)}(t) \quad (7c) \]

\[ P_2^{(b)}(t) : \quad \text{Ratio of processed milk/dairy to consumed milk/dairy} \]

\[ A_{43}^{(i)}(t) = P_3^{(b)}(t)A_{35}^{(i)}(t) \quad (7f) \]

\[ P_3^{(b)}(t) : \quad \text{Ratio of processed vegetable to consumed vegetable} \]

\[ \ldots \]

Organic waste from household

\[ O_4(t) = P_4^{(b)}(t)\sum_{j=1}^{4} (A_{43}^{(j)}(t) - A_{35}^{(j)}(t)) + P_5^{(b)}(t)(A_{43}^{(5)}(t) - A_{35}^{(5)}(t)) + P_6^{(b)}(t)\sum_{j=6}^{11} (A_{43}^{(j)}(t) - A_{35}^{(j)}(t)) \]

(7m)
where

\[ P_4^{(h)}(t) : \text{Transfercoefficient to organic waste from meat waste in household} \]

\[ P_5^{(h)}(t) : \text{Transfercoefficient to organic waste from milk/dairy waste in household} \]

\[ P_6^{(h)}(t) : \text{Transfercoefficient to organic waste from vegetable waste in household} \]

Organic waste as fodder from household:

\[
A_{31}(t) = P_7^{(h)}(t) \sum_{j=1}^{4} (A_{43}^{(j)}(t) - A_{35}^{(j)}(t)) + P_8^{(h)}(t)(A_{43}^{(5)}(t) - A_{35}^{(5)}(t)) + P_9^{(h)}(t) \sum_{j=6}^{11} (A_{43}^{(j)}(t) - A_{35}^{(j)}(t))
\]

(7n)

where:

\[ P_7^{(h)}(t) : \text{Transfercoefficient to fodder from meat waste in household} \]

\[ P_8^{(h)}(t) : \text{Transfercoefficient to fodder from milk/dairy waste in household} \]

\[ P_9^{(h)}(t) : \text{Transfercoefficient to fodder from vegetable waste in household} \]

No stock accumulation in household:

\[ \dot{M}^{(3)}(t) = 0 \quad (7o) \]

D. Food processing:

Produced food related to processed food:

\[ A_{14}^{(i)}(t) = P_1^{(p)} A_{43}^{(i)}(t) \quad (8a) \]

\[ P_1^{(p)}(t) : \text{Ratio of produced meat to processed meat} \]

\[ \ldots \]

\[ A_{14}^{(5)}(t) = P_2^{(p)} A_{43}^{(5)}(t) \quad (8e) \]

\[ P_2^{(p)}(t) : \text{Ratio of produced milk/dairy to processed milk/dairy} \]

\[ A_{14}^{(6)}(t) = P_3^{(p)} A_{43}^{(6)}(t) \quad (8f) \]

\[ P_3^{(p)}(t) : \text{Ratio of produced vegetable to processed vegetable} \]

\[ \ldots \]

Organic waste as fertilizer from processing:

\[
A_{42}(t) = P_4^{(p)}(t) \sum_{j=1}^{4} (A_{14}^{(j)}(t) - A_{43}^{(j)}(t)) + P_5^{(p)}(t)(A_{14}^{(5)}(t) - A_{43}^{(5)}(t)) + P_6^{(p)}(t)(A_{14}^{(6)}(t) - A_{43}^{(6)}(t)) + \sum_{j=7}^{11} (A_{24}^{(j-6)}(t) - A_{43}^{(j)}(t))
\]

(8m)

where:

\[ P_4^{(p)}(t) : \text{Transfercoefficient to fertilizer from waste in processing of meat} \]

\[ P_5^{(p)}(t) : \text{Transfercoefficient to fertilizer from waste in processing of milk/dairy} \]

\[ P_6^{(p)}(t) : \text{Transfercoefficient to fertilizer from waste in processing of vegetable} \]
Organic waste as fodder from processing:

\[
A_{41}(t) = P_{7}^{(p)}(t) \sum_{j=1}^{4} (A_{14}^{(j)}(t) - A_{43}^{(j)}(t)) + P_{8}^{(p)}(t)(A_{14}^{(5)}(t) - A_{43}^{(5)}(t)) + P_{9}^{(p)}(t)((A_{14}^{(6)}(t) - A_{43}^{(6)}(t)) + \sum_{j=7}^{11} (A_{24}^{(j-6)}(t) - A_{43}^{(j)}(t)))
\]

(8n)

where:

\[
\begin{align*}
P_{7}^{(p)}(t) & : \text{Transfercoefficient to fodder from waste in processing of meat} \\
P_{8}^{(p)}(t) & : \text{Transfercoefficient to fodder from waste in processing of milk/dairy} \\
P_{9}^{(p)}(t) & : \text{Transfercoefficient to fodder from waste in processing of vegetable}
\end{align*}
\]

No stock accumulation in food processing:

\[
\dot{M}^{(4)}(t) = 0 \quad (8o)
\]

E. Vegetable production:

Manure:

\[
A_{12}(t) = P_{1}^{(v)}(t) \sum_{j=1}^{5} (A_{24}^{(j)}(t) - A_{14}^{(j)}(t)) - \sum_{j=7}^{6} P_{2}^{(v)}(t) P_{2}^{(v)}(t_{j+1}) A_{14}^{(j)}(t) - A_{32}(t) - A_{42}(t) - A_{62}(t)
\]

(9a)

where

\[
\begin{align*}
P_{1}^{(v)}(t) & : \text{Specific manure for vegetable production} \\
P_{2}^{(v)}(t) & : \text{Specific manure for fodder for beef} \\
P_{3}^{(v)}(t) & : \text{Specific fodder for beef}
\end{align*}
\]

Fodder:

\[
A_{21}(t) = \sum_{j=1}^{6} P_{2}^{(v)}(t_{j+1}) A_{14}^{(j)}(t) \quad (9b)
\]

\[
P_{3}^{(v)}(t), P_{5}^{(v)}(t), ..., P_{13}^{(v)}(t) \quad \text{see equation (9a) above}
\]

Fixation:

\[
I_{1}(t) = \sum_{j=1}^{6} P_{13}^{(v)}(t_{j+1}) A_{14}^{(j)}(t) + P_{20}^{(v)}(t) \sum_{j=1}^{5} A_{24}^{(j)}(t) \quad (9c)
\]

where:

\[
\begin{align*}
P_{14}^{(v)}(t) & : \text{Specific fixation and deposition to fodder for beef} \\
& \cdots \\
P_{19}^{(v)}(t) & : \text{Specific fixation and deposition to fodder for egg production} \\
P_{20}^{(v)}(t) & : \text{Specific fixation and deposition to vegetable production}
\end{align*}
\]
Chemical fertilizer: (similar to fixation)

\[ I_2(t) = \sum_{j=1}^{6} P_{20,j}^{(v)}(t) \cdot P_{2,j+1}^{(v)}(t) A_{14}^{(j)}(t) + P_{27}^{(v)}(t) \sum_{j=1}^{5} A_{24}^{(j)}(t) \quad (9d) \]

where

- \( P_{21}^{(v)}(t) \) : Specific chemical fertilizer for fodder for beef production
- \( P_{26}^{(v)}(t) \) : Specific chemical fertilizer for fodder for egg production
- \( P_{27}^{(v)}(t) \) : Specific chemical fertilizer for vegetable production

Emission from agriculture:

\[ O_6(t) = \sum_{j=1}^{6} P_{21,j}^{(v)}(t) \cdot P_{2,j+1}^{(v)}(t) A_{14}^{(j)}(t) + P_{27}^{(v)}(t) \sum_{j=1}^{5} A_{24}^{(j)}(t) \quad (9e) \]

where:

- \( P_{28}^{(v)}(t) \) : Specific emission from fodder for beef production
- \( P_{33}^{(v)}(t) \) : Specific emission from fodder for egg production
- \( P_{34}^{(v)}(t) \) : Specific emission from vegetable production

Leakage from agriculture:

\[ O_7(t) = \sum_{j=1}^{6} P_{34,j}^{(v)}(t) \cdot P_{2,j+1}^{(v)}(t) A_{14}^{(j)}(t) + P_{41}^{(v)}(t) \sum_{j=1}^{5} A_{24}^{(j)}(t) \quad (9f) \]

where:

- \( P_{35}^{(v)}(t) \) : Specific leakage from fodder for beef production
- \( P_{40}^{(v)}(t) \) : Specific leakage from fodder for egg production
- \( P_{41}^{(v)}(t) \) : Specific leakage from vegetable production

F. Animal production:

No stock accumulation in animal production:

\[ \dot{M}^{(0)}(t) = 0 \quad (10a) \]

Emissions from animal production:

\[ O_8(t) = P_1^{(a)}(t)(O_8(t) + O_8(t)) \quad (10b) \]

\( P_1^{(a)}(t) \): Ammonia emission factor
The model approach consists of the 53 equations (5)-(10), containing the 76 parameter functions

\( P_1^{(w)}, \ldots, P_1^{(a)} \). Note that the superscripts (w), (c), (h), (p), (v), and (a) refer to the 6 processes: waste processing, consumer, household, processing of food, plant and animal production.

The model approach was designed for nitrogen as well as for phosphorus. For phosphorus, in contrast to nitrogen, the 3 emissions into the atmosphere are 0. Mathematically this means that the corresponding parameter functions have to be 0, namely:

- \( O_2 \): Emissions from waste into atmosphere: eq (5c)
  \[ P_3^{(w)}(t) = 0 \]
- \( O_6 \): Emissions from agriculture into atmosphere: eq (9e)
  \[ P_6^{(w)}(t) = \ldots = P_6^{(w)}(t) = 0 \]
- \( O_5 \): Emissions from animal production into atmosphere: eq (10b)
  \[ P_1^{(a)}(t) = 0 \]

iv) Equations for the auxiliary variables:

Area used for animal production:

\[ H_1(t) = \sum_{j=1}^{6} P_j^{(h)}(t) \cdot A_{4j}(t) \quad (11a) \]

\( P_j^{(h)}(t) \): Fodder area for beef,\ldots, egg-production

Area used for vegetable production:

\[ H_2(t) = P_6^{(h)}(t) \sum_{j=1}^{5} A_{24j}(t) \quad (11b) \]

\( P_6^{(h)}(t) \): Vegetable production area

Total area used for food production:

\[ H_3(t) = H_1(t) + H_2(t) \quad (11c) \]

Sum of meat consumption:

\[ H_4(t) = \sum_{j=4}^{6} A_{35j}(t) \quad (11d) \]

Sum of vegetable consumption:

\[ H_5(t) = \sum_{j=1}^{11} A_{35j}(t) \quad (11e) \]

Sum of total consumption:

\[ H_6(t) = H_4(t) + H_5(t) \quad (11f) \]

Sum of meat production:

\[ H_7(t) = \sum_{j=4}^{6} A_{44j}(t) \quad (11g) \]
Sum of vegetable production:

\[ H_8(t) = \sum_{j=1}^{5} A_{24}^{(j)}(t) \]  

(11h)

Sum of all reuse flows:

\[ H_9(t) = A_{62}(t) + A_{63}(t) + A_{31}(t) + A_{32}(t) + A_{42}(t) + A_{41}(t) \]  

(11i)

Sum of all losses:

\[ H_{10}(t) = O_1(t) + O_2(t) + O_3(t) + O_4(t) + O_5(t) \]  

(11j)

Ratio of all reuse/all losses and all losses/all reuse:

\[ H_{11}(t) = \frac{H_8(t)}{H_{10}(t)} \]  

(11k)

\[ H_{12}(t) = \frac{H_{10}(t)}{H_8(t)} \]  

(11l)

Sum of reuse flows waste:

\[ H_{13}(t) = A_{62}(t) + A_{61}(t) \]  

(11m)

Sum of losses of waste:

\[ H_{14}(t) = O_1(t) + O_2(t) + O_3(t) \]  

(11n)

Ratio of waste reuse/waste losses and waste losses/waste reuse:

\[ H_{15}(t) = \frac{H_{13}(t)}{H_{14}(t)} \]  

(11o)

\[ H_{16}(t) = \frac{H_{14}(t)}{H_{13}(t)} \]  

(11p)
Calibration

Figure A1: Examples of parameter functions for linear, spline and cubic interpolation for nitrogen.
Figure A2: Examples of parameter functions for linear, spline and cubic interpolation for phosphorus.
The smoothing procedure is Gaussian:

\[ X_i^{(s)}(t_n) = \frac{1}{N_n} \sum_{j=-n}^{n} X_i(t_{n+j}) e^{-\frac{(t_n-t_{n+j})^2}{2\sigma^2}} \]

\[ N_n = \sum_{j=-n}^{n} e^{-\frac{(t_n-t_{n+j})^2}{2\sigma^2}} \]

where:

- \( X_i(t_n) \): Variable \( X_i \) at time \( t_n \)
- \( X_i^{(s)}(t_n) \): Smoothed variable \( X_i \) at time \( t_n \)
- \( n \): Smoothing range (selectable)
- \( \sigma \): Smoothing strength (selectable)
- \( t_n \): Time points \( n=1,2,\ldots \)
- \( N_n \): Normalization factor

A typical example for the smoothing function \( e^{-\frac{(t_n-t_{n+j})^2}{2\sigma^2}} \) is shown in Figure A3.

Figure A3: Example for the smoothing function; spline.
Appendix B: System II

1. System variables
The following variables describe the system shown in figure 5.6 completely:

Stocks:
\[ M^{(i)} : \text{Human consumption} \]
\[ \ldots (13) \]
\[ M^{(10)} : \text{Energy system/Energy forest} \]

Flows:
Human consumption:
\[ I_1 : \text{Vegetable food consumption} \]
\[ I_2 : \text{Animal food consumption} \]
\[ A_{12} : \text{Faeces} \]
\[ A_{13} : \text{Urine} \]

Faeces collection:
\[ A_{24} : \text{Faeces to waste} \]
\[ A_{26} : \text{Faeces loss} \]

Urine collection:
\[ A_{34} : \text{Urine to waste} \]
\[ A_{39} : \text{Urine to soil} \]
\[ A_{36} : \text{Urine loss} \]

Waste handling:
\[ A_{46} : \text{Nutrient loss from waste} \]
\[ A_{45}^{(1)} : \text{Waste to sludge faeces} \]
\[ A_{45}^{(2)} : \text{Waste to sludge urine} \]
\[ A_{48}^{(1)} : \text{Feed faeces} \]
\[ A_{48}^{(2)} : \text{Feed urine} \]
\[ A_{49}^{(1)} : \text{Faeces fertilizer from waste} \]
\[ A_{49}^{(2)} : \text{Urine fertilizer from waste} \]

Sludge handling:
\[ A_{56} : \text{Nutrient loss from sludge} \]
\[ A_{57} : \text{Sludge to landfill} \]
\[ A_{59} : \text{Fertilizer from sludge} \]
\[ A_{510} : \text{Sludge to energy system/energy forest} \]

Auxiliary variables:
\[ H_1 : \text{Total food consumption} \]
\[ H_2 : \text{Total waste to sludge} \]
\[ H_3 : \text{Total feed} \]
\( H_4 \): Total fertilizer from waste
\( H_5 \): Reuse to plants, soil
\( H_6 \): Reuse to livestock, plants, soil
\( H_7 \): Total reuse
\( H_8 \): Losses to hydrosphere
\( H_9 \): Losses total
\( H_{10} \): Ratio of reuse to livestock/plant/soil to total losses
\( H_{11} \): Ratio of total losses to reuse to livestock/plant/soil
\( H_{12} \): Ratio of total reuse to total losses
\( H_{13} \): Ratio of total losses to total reuse
\( H_{14} \): Ratio of reuse to livestock to reuse to plant/soil

Including the stock change rates, these are 54 variables in total.

2. Model equations

As in system I the system knowledge was gained during the study to quantify the system of waste handling. This suggested that an input-output approach should adequately describe the system in a first approximation. Hereby the transfercoefficients represent again the technical and natural conditions of the system. For simplicity, the intrinsic and balance equations have been omitted.

Model approach

A. Human consumption:

Consumption of vegetable and animal food:

\[ I_1(t) = PW^{(c)}_1(t) \] (15a)
\[ I_2(t) = PW^{(c)}_2(t) \] (15b)
\( PW^{(c)}_1(t) \): Consumption of vegetable food
\( PW^{(c)}_2(t) \): Consumption of animal food

Faeces:

\[ A_{12}(t) = PW^{(c)}_3(t)I_1(t) + PW^{(c)}_4(t)I_2(t) \] (15c)
\( PW^{(c)}_3(t) \): Transfercoefficients of veg. food to faeces
\( PW^{(c)}_4(t) \): Transfercoefficient of anim. food to faeces

Urine:

\[ A_{13}(t) = PW^{(c)}_5(t)I_1(t) + PW^{(c)}_6(t)I_2(t) \] (15d)
\( PW^{(c)}_5(t) \): Transfercoefficients of veg. food to urine
\( PW^{(c)}_6(t) \): Transfercoefficient of anim. food to urine

B. Faeces collection:

No stock accumulation

\[ M^{(2)}(t) = 0 \] (16a)
Faeces to secondary treatment
\[ A_{24}(t) = P_{w1}^{(f)}(t) \cdot A_{12}(t) \quad (16b) \]

\[ P_{w1}^{(f)}(t) \]: Transfercoefficient of faeces collection to secondary treatment

C. Urine collection:

No stock accumulation
\[ \dot{M}^{(3)}(t) = 0 \quad (17a) \]

Urine to secondary treatment
\[ A_{34}(t) = P_{w1}^{(u)}(t) \cdot A_{13}(t) \quad (17b) \]

\[ P_{w1}^{(u)}(t) \]: Transfercoefficient of urine collection to secondary treatment

Urine to plants and soil
\[ A_{39}(t) = P_{w2}^{(u)}(t) \cdot A_{13}(t) \quad (17c) \]

\[ P_{w2}^{(u)}(t) \]: Transfercoefficient of urine collection to plants and soil

D. Secondary treatment

No stock accumulation
\[ \dot{M}^{(4)}(t) = 0 \quad (18a) \]

Waste to sludge
\[ A_{45}^{(1)}(t) = P_{w1}^{(w)}(t) \cdot A_{24}(t) \quad (18b) \]

\[ P_{w1}^{(w)}(t) \]: Transfercoefficient of faeces to sludge handling

\[ A_{45}^{(2)}(t) = P_{w2}^{(w)}(t) \cdot A_{34}(t) \quad (18c) \]

\[ P_{w2}^{(w)}(t) \]: Transfercoefficient of urine to sludge handling

Waste to livestock
\[ A_{48}^{(1)}(t) = P_{w3}^{(w)}(t) \cdot A_{24}(t) \quad (18d) \]

\[ P_{w3}^{(w)}(t) \]: Transfercoefficient of faeces to livestock

\[ A_{48}^{(2)}(t) = P_{w4}^{(w)}(t) \cdot A_{34}(t) \quad (18e) \]

\[ P_{w4}^{(w)}(t) \]: Transfercoefficient of urine to livestock

Waste to plants/soil
\[ A_{49}^{(1)}(t) = P_{w5}^{(w)}(t) \cdot A_{24}(t) \quad (18f) \]

\[ P_{w5}^{(w)}(t) \]: Transfercoefficient of faeces to plants/soil

\[ A_{49}^{(2)}(t) = P_{w6}^{(w)}(t) \cdot A_{34}(t) \quad (18g) \]

\[ P_{w6}^{(w)}(t) \]: Transfercoefficient of urine to plants/soil

E. Sludge handling

No stock accumulation
\[ \dot{M}^{(5)}(t) = 0 \quad (19a) \]

Sludge as fertilizer
\[ A_{50}(t) = P_{w1}^{(f)}(t) \cdot (A_{45}^{(1)}(t) + A_{45}^{(2)}(t)) \quad (19b) \]

\[ P_{w1}^{(f)}(t) \]: Transfercoefficient of sludge to plants/soil

Sludge to energy system/energy forest
\[ A_{510}(t) = P_{w2}^{(f)}(t) \cdot (A_{45}^{(1)}(t) + A_{45}^{(2)}(t)) \quad (19c) \]
\(PW_2^{(*)}(t)\): Transfer coefficient of sludge to energy system/energy forest

Deposition of sludge

\[A_{s7}(t) = PW_3^{(*)}(t) \cdot (A_{45}^{(1)}(t) + A_{45}^{(2)}(t)) \quad (19d)\]

\(PW_3^{(*)}(t)\): Transfer coefficient of sludge to landfill

Equations for the auxiliary variables:

Total food consumption:

\[H_1(t) = I_1(t) + I_2(t) \quad (20a)\]

Total waste to sludge:

\[H_2(t) = A^{(1)}_{45}(t) + A^{(2)}_{45}(t) \quad (20b)\]

Total food:

\[H_3(t) = A^{(1)}_{49}(t) + A^{(2)}_{49}(t) \quad (20c)\]

Total fertilizer from waste:

\[H_4(t) = A^{(1)}_{49}(t) + A^{(2)}_{49}(t) \quad (20d)\]

Reuse to plant/soil:

\[H_5(t) = A_{39}(t) + A^{(1)}_{49}(t) + A^{(2)}_{49}(t) + A_{59}(t) \quad (20e)\]

Reuse to livestock, plant/soil:

\[H_6(t) = H_5 + A^{(1)}_{48}(t) + A^{(2)}_{48}(t) \quad (20f)\]

Reuse total:

\[H_7(t) = H_6(t) + A_{510}(t) \quad (20g)\]

Losses to hydrosphere:

\[H_8(t) = A_{36}(t) + A_{36}(t) + A_{46}(t) + A_{46}(t) \quad (20h)\]

Losses total:

\[H_9(t) = H_8(t) + A_{57}(t) \quad (20i)\]

Ratio of reuse to livestock/plant/soil to total losses:

\[H_{10}(t) = \frac{H_6(t)}{H_9(t)} \quad (20j)\]

\[H_{11}(t) = \frac{H_9(t)}{H_6(t)} \quad (20k)\]

Ratio of total reuse to total losses:

\[H_{12}(t) = \frac{H_7(t)}{H_9(t)} \quad (20l)\]

\[H_{13}(t) = \frac{H_9(t)}{H_7(t)} \quad (20m)\]

Ratio of reuse for livestock to reuse to plant/soil:

\[H_{14}(t) = \frac{H_3(t)}{H_5(t)} \quad (20n)\]
Calibration
The procedure is similar as for System I in appendix A.

Appendix C: Uncertainty analysis

System I
For system I, three cases are presented, for the calculations of nitrogen and phosphorus each.

**Case 1:** Uncertainty of 20% (Level 2) in all food consumption for 1870 and 1900 and an uncertainty of 10% (Level 1) in all food consumption for 1950 and 2000

**Case 2:** Uncertainty of 30% (Level 3) in all fodder input for 1870 and 1900, and an uncertainty of 20% (Level 2) for 1950, and 10% (Level 1) in all fodder input for 2000

**Case 3:** Uncertainty of 20% for all food consumption for 1870 and 1900, and 10% for all food consumption and fodder input for 1950 and 2000; and an uncertainty of 30% (Level 3) in all fodder input for 1870 and 1900, 20% (Level 2) for 1950, and 10% (Level 1) in all fodder input for 2000.

Some variables were selected. They were calculated with a quadratic spline function, and smoothed in order to avoid roughness in the graphic presentation of results. The black lines indicate the average value; the gray lines indicate the uncertainty margin. X refers to the number of the variable in the system.
Figure C1: Case I for the flow of nitrogen. All flows are in kg N/capita per year.
Figure C.5: Case II for the flow of nitrogen. All flows are in kg N/capita per year. Note: X 14 (emissions from waste to hydrosphere) is not effected in this case.
Figure C3: Case III for the flow of nitrogen. All flows are in kg N/capita per year.
Figure C4: Case I for the flow of phosphorus. All flows are in kg P/capita per year.
Figure C.5: Case II for the flow of phosphorus. All flows are in kg P/capita per year. Note: X 14 (emissions from waste to hydrosphere) is not affected in this case.
Figure C.6: Case III for the flow of phosphorus. All flows are in kg P/capita per year.
System II

For system II, two cases of uncertainty calculations are presented

**Case I**: Uncertainty of 20% (Level 2) in all food consumption for 1870, 1885, 1900, 1920, 1940, uncertainty of 10% (Level 1) for 1950, 1975, 1990 and 2000.

**Case II**: Direct comparison of the range given in the input data (see Appendix D) for the processes of secondary waste treatment and sludge handling.

Three variables were chosen as examples, based on their relevance for the analysis. The black lines indicate the average value; the gray lines indicate the uncertainty margin. X refers to the number of the variable in the system.

**Case I**:

Figure C. Case I for the flow of phosphorus. All flows are in kg P/capita per year.

**Case II**:

Figure C. Case II for the flow of phosphorus. All flows are in kg P/capita per year.
Appendix D: Data and Assumptions

Uncertainties/Ranges

If a specific range is given, the mean value is applied in the calculations.

Uncertainties are in the following represented as 'level' 1-5 (cf Hedbrant and Sörme 2000)

<table>
<thead>
<tr>
<th>Level</th>
<th>Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>±10%</td>
</tr>
<tr>
<td>2</td>
<td>±20%</td>
</tr>
<tr>
<td>3</td>
<td>±30%</td>
</tr>
<tr>
<td>4</td>
<td>±40%</td>
</tr>
<tr>
<td>5</td>
<td>±50%</td>
</tr>
</tbody>
</table>

Table D1: The City and its Sanitary System

<table>
<thead>
<tr>
<th>Year</th>
<th>No of inhabitants</th>
<th>Primary waste treatment/ toilet system</th>
<th>Comments</th>
<th>Secondary waste treatment or storage</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1870</td>
<td>7 300</td>
<td>0% WC; 10% water-tight buckets; 90% dug pit/outhouse</td>
<td>Level 3 based on (1)</td>
<td>70-90% to soil; 10-30% to animal fodder</td>
<td></td>
</tr>
<tr>
<td>1885</td>
<td>10 700</td>
<td>2% WC; 5% urine separation; 30% water-tight buckets; 63% dug pit or equiv.</td>
<td>Level 3 based on (1)</td>
<td>80-100% to soil; 0-20% to animal fodder</td>
<td></td>
</tr>
<tr>
<td>1900</td>
<td>14 500</td>
<td>8% WC; 16% urine separation; 76% water-tight buckets; 0% pit latrine or equiv.</td>
<td>Level 3 based on (1)</td>
<td>80-100% to soil; 0-20% to animal fodder</td>
<td></td>
</tr>
<tr>
<td>1920</td>
<td>26 900</td>
<td>20% WC; 10% urine separation; 70% water-tight buckets</td>
<td>Level 3 based on (2)</td>
<td>95-100% to soil; 0-5% to animal fodder</td>
<td></td>
</tr>
<tr>
<td>1940</td>
<td>38 650</td>
<td>50% WC; 0% urine separation; 50% water-tight buckets</td>
<td>Level 2 (3)</td>
<td>40-60% to soil; 40-60% to landfill</td>
<td></td>
</tr>
<tr>
<td>1950</td>
<td>54 500</td>
<td>90% WC; 10% water-tight buckets</td>
<td>Level 2 (4) wastewater treatment plant (WWTP), mechanical treatment. 60% of WC connected to WWTP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1975</td>
<td>78 000</td>
<td>100% WC</td>
<td>(6), (7) WWTP with 90% of P to sludge; 0-20% to plant/soil</td>
<td>All WC connected to WWTP</td>
<td></td>
</tr>
<tr>
<td>1990</td>
<td>82 600</td>
<td>100% WC</td>
<td>(5), (7), (9) WWTP with 95% of P to sludge; 20-30% reused (of which 2/3 to energy forest and 1/3 to farmers); 70-80% to landfill</td>
<td>same assumptions as for the year 2000 (Level 2)</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>94 000</td>
<td>100% WC</td>
<td>(5), (8), (9) WWTP with 97% of P and 58% of N to sludge. 21% reused (10-40%) (of which 2/3 to energy forest and 1/3 to farmers); 79% to landfill</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


The proportion of phosphorus in faeces and urine was obtained from Naturvårdsverket 1995.
Note: slight variations in the results for waste handling of system I and II occur due to a more explicit system definition in system II, where faeces and urine are separately calculated and additional losses could be included.

**Table D2: Waste household processing** (Transfer data)

<table>
<thead>
<tr>
<th>Food</th>
<th>Aim-process</th>
<th>1870</th>
<th>1900</th>
<th>1950</th>
<th>2000</th>
<th>Assumptions/Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meat</td>
<td>Total input</td>
<td>1-1.4</td>
<td>1-1.4</td>
<td>1-1.4</td>
<td>1-1.4</td>
<td>Due to lack of data, all based on (1)</td>
</tr>
<tr>
<td>Meat</td>
<td>Animal prod</td>
<td>0.8-1</td>
<td>0.8-1</td>
<td>0.2</td>
<td>0.1</td>
<td>Assumptions; based on (1), (2); (Level 2 for 1950, 2000)</td>
</tr>
<tr>
<td>Meat</td>
<td>Waste handling</td>
<td>0</td>
<td>0</td>
<td>0.8</td>
<td>0.9</td>
<td>Assumptions; (1); (Level 2 for 1950, 2000)</td>
</tr>
<tr>
<td>Milk</td>
<td>Total input</td>
<td>1-1.04</td>
<td>1-1.04</td>
<td>1-1.04</td>
<td>1-1.04</td>
<td>Due to lack of data, all based on (1)</td>
</tr>
<tr>
<td>Milk</td>
<td>Animal prod</td>
<td>0.8-1</td>
<td>0.8-1</td>
<td>0.1</td>
<td>0.05</td>
<td>Assumptions; (Level 2 for 1950, 2000)</td>
</tr>
<tr>
<td>Milk</td>
<td>Waste handling</td>
<td>0</td>
<td>0</td>
<td>0.9</td>
<td>0.95</td>
<td>Assumptions; (Level 2)</td>
</tr>
<tr>
<td>Veg</td>
<td>Total input</td>
<td>1-1.6</td>
<td>1-1.6</td>
<td>1-1.4</td>
<td>1-1.4</td>
<td>Based on (1); assumption no industrial processing in 1870/1900</td>
</tr>
<tr>
<td>Veg</td>
<td>Animal prod</td>
<td>0.6-1</td>
<td>0.6-1</td>
<td>0.1</td>
<td>0.05</td>
<td>Assumption; (Level 2 for 1950, 2000)</td>
</tr>
<tr>
<td>Veg</td>
<td>Waste handling</td>
<td>0</td>
<td>0</td>
<td>0.8</td>
<td>0.85</td>
<td>Assumption; (Level 2 for 1950, 2000)</td>
</tr>
<tr>
<td>Veg</td>
<td>Plant prod</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>Assumption; (Level 2)</td>
</tr>
</tbody>
</table>

Sources: (1) Carlsson-Kanyama and Faist 2000; (2) Schüle 1989

**Table D3: Waste industrial processing** (Transfer data)

<table>
<thead>
<tr>
<th>Food</th>
<th>Aim-process</th>
<th>1870</th>
<th>1900</th>
<th>1950</th>
<th>2000</th>
<th>Assumptions/Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meat</td>
<td>Total input</td>
<td>1</td>
<td>1</td>
<td>1.3</td>
<td>1.3</td>
<td>Assumption/Swedish average (1); (Level 2)</td>
</tr>
<tr>
<td>Meat</td>
<td>Animal prod</td>
<td>0</td>
<td>0</td>
<td>0.6-1</td>
<td>0.6-1</td>
<td>No processing in 1870/1900; assumption based on (2)</td>
</tr>
<tr>
<td>Meat</td>
<td>Waste handling</td>
<td>0</td>
<td>0</td>
<td>0.4</td>
<td>0.4</td>
<td>No processing in 1870/1900; assumption based on (2)</td>
</tr>
<tr>
<td>Milk</td>
<td>Total input</td>
<td>1.36(P)</td>
<td>1.49(P)</td>
<td>1.79(P)</td>
<td>1.82(P)</td>
<td>Average for dairy prod for P and N (based on 1; 3); (Level 3)</td>
</tr>
<tr>
<td>Milk</td>
<td>Animal prod</td>
<td>1</td>
<td>1</td>
<td>0.6-1</td>
<td>0.6-1</td>
<td>No processing in 1870/1900; assumptions based on (2)</td>
</tr>
<tr>
<td>Milk</td>
<td>Waste handling</td>
<td>0</td>
<td>0</td>
<td>0.4</td>
<td>0.4</td>
<td>No processing in 1870/1900; assumptions 1950 as 2000, based on (2); (Level 1)</td>
</tr>
<tr>
<td>Veg</td>
<td>Total input</td>
<td>1</td>
<td>1</td>
<td>1.3</td>
<td>1.3</td>
<td>No processing in 1870/1900; based on (1); (Level 2)</td>
</tr>
<tr>
<td>Veg</td>
<td>Animal prod</td>
<td>0</td>
<td>0</td>
<td>0.15</td>
<td>0.15</td>
<td>No processing in 1870/1900; assumptions 1950 as 2000, based on (2); (Level 2)</td>
</tr>
<tr>
<td>Veg</td>
<td>Waste handling</td>
<td>0</td>
<td>0</td>
<td>0.05</td>
<td>0.05</td>
<td>No processing in 1870/1900; assumptions 1950 as 2000, based on (2); (Level 2).</td>
</tr>
<tr>
<td>Veg</td>
<td>Plant prod</td>
<td>0</td>
<td>0</td>
<td>0.6-1</td>
<td>0.6-1</td>
<td>No processing in 1870/1900; assumptions 1950 as 2000, based on (2)</td>
</tr>
</tbody>
</table>

Sources: (1) Carlsson-Kanyama and Faist 2000; (2) Naturvårdsverket 1996 (3) SLV 1990.
Table D.4: Animal production

<table>
<thead>
<tr>
<th>Product</th>
<th>Year</th>
<th>Kg fodder/kg product</th>
<th>Fodder</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beef</td>
<td>1870</td>
<td>26 (Level 3)</td>
<td>52% pasture, 8% cereal, 40% coarse fodder; (Level 5)</td>
<td>(1)</td>
</tr>
<tr>
<td></td>
<td>1900</td>
<td>22 (Level 3)</td>
<td>28% pasture, 59% cereal, 13% coarse fodder/protein fodder; (Level 3)</td>
<td>(2)</td>
</tr>
<tr>
<td></td>
<td>1950</td>
<td>10-16</td>
<td>25% pasture, 28% cereal, 45% coarse fodder, 2% protein; (Level 1)</td>
<td>(3)</td>
</tr>
<tr>
<td>Pork</td>
<td>1870</td>
<td>9 (Level 3)</td>
<td>20% cereal, 2% protein fodder, 2% pasture, 2% root crops, 74% org waste; (Level 5) (1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1900</td>
<td>8 (Level 3)</td>
<td>20% cereal, 1% protein fodder, 9% root crops, 52% org waste; (Level 3) (2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1950</td>
<td>5 (Level 2)</td>
<td>38% cereal, 1% protein fodder, 9% root crops, 52% org waste; (Level 3) (2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>4.5 (Level 1)</td>
<td>85% cereal, 15% protein fodder; (Level 1) (3),(4)</td>
<td></td>
</tr>
<tr>
<td>Poultry</td>
<td>1870-1900</td>
<td>n.a.</td>
<td>74% cereal, 17% protein fodder, 9% org waste; (Level 3)</td>
<td>(2)</td>
</tr>
<tr>
<td></td>
<td>1950</td>
<td>3.5 (Level 2)</td>
<td>74% cereal, 17% protein fodder, 9% org waste; (Level 1)</td>
<td>(4)</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>2.9</td>
<td>74% cereal, 17% protein fodder, 9% org waste; (Level 1)</td>
<td></td>
</tr>
<tr>
<td>Fish</td>
<td>1950</td>
<td>1 (Level 3)</td>
<td>10% cereal (assumed low share of aquaculture); (Level 3) Assumed same as 2000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>1 (Level 2)</td>
<td>20% cereal; (assumed low share of aquaculture); (Level 2) (5); Salmon and trout</td>
<td></td>
</tr>
<tr>
<td>Milk</td>
<td>1870</td>
<td>2.7 (Level 2)</td>
<td>53% cereal, 19% coarse fodder, 12% protein fodder, 12% pasture, 4% root crops; (Level 3) Assumption based on (1)</td>
<td>(1)</td>
</tr>
<tr>
<td></td>
<td>1900</td>
<td>2.3 (Level 2)</td>
<td>35% cereal, 15% coarse fodder, 5% protein fodder, 34% pasture, 11% root crops; (Level 2) (1); (2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1950</td>
<td>1.5 (Level 2)</td>
<td>26% cereal, 47% coarse fodder, 11% protein fodder, 16% pasture; (Level 1) (3), (4)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>0.8</td>
<td>26% cereal, 47% coarse fodder, 11% protein fodder, 16% pasture; (Level 1) (3), (4)</td>
<td></td>
</tr>
<tr>
<td>Egg</td>
<td>1870</td>
<td>n.a.</td>
<td>Assumed same as 1950; (Level 5)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1900</td>
<td>6.6 (Level 3)</td>
<td>Assumed same as 1950; (Level 5)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1950</td>
<td>4 (Level 2)</td>
<td>70% cereal, 25% protein rich fodder, 5% org waste; (Level 2) (2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>2.4</td>
<td>70% cereal, 25% protein rich fodder, 5% org waste; (Level 1) (1)</td>
<td>(4)</td>
</tr>
</tbody>
</table>

Sources: (1) HÖ 1869-1951; (2) Norin 1963; (3) SLU 1996; (4) Naturvårdsvetet 1997c; (5) Carlsson-Kanyama and Faist 2000

Assumptions: Amounts of N and P in fodder were obtained from SJV 2003b, pasture from Hoffman 1999. Since no historical data was available, the same average was assumed to be valid for all years. This might contribute to the smaller average area for food production in system I. Furthermore, internal reuse of slaughter carcass as fodder was assumed in animal production for beef and pork with 5% and 10% respectively in 1870 and 1900. The consumption of lamb meat was added to the beef production, due to its small proportion of the total meat consumption (around 1%) and a lack of data on production and fodder. Horse, reindeer and game were not included into the calculations. Reason for this was the low share of these to the total meat consumption (less than 4% for horse and reindeer meat in 1950 and less than 1% in 2000) and lack of information on production and fodder. Game was not considered livestock.
### Table D5: Nitrogen Data: Plant production

<table>
<thead>
<tr>
<th>Source</th>
<th>Amount N in kg/ha</th>
<th>Year</th>
<th>Uncertainty range</th>
<th>Comments</th>
<th>Comments</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manure</td>
<td>9-10</td>
<td>1870-2000</td>
<td>(Level 1-3)</td>
<td>Due to lack of historical information, the value for 2000 was assumed valid for the entire period.</td>
<td></td>
<td>(2)</td>
</tr>
<tr>
<td>Manure</td>
<td>13.7</td>
<td>1865/75</td>
<td>(Level 3)</td>
<td>Sum of ammonium and organic nitrogen</td>
<td></td>
<td>(1)</td>
</tr>
<tr>
<td>Manure</td>
<td>14.15</td>
<td>1895/1900</td>
<td>(Level 3)</td>
<td>Sum of ammonium and organic nitrogen</td>
<td></td>
<td>(1)</td>
</tr>
<tr>
<td>Manure</td>
<td>15.8</td>
<td>1945/1955</td>
<td>(Level 2)</td>
<td>Sum of ammonium and organic nitrogen</td>
<td></td>
<td>(1)</td>
</tr>
<tr>
<td>Manure</td>
<td>21.1</td>
<td>1985</td>
<td>(Level 1)</td>
<td>Sum of ammonium and organic nitrogen</td>
<td></td>
<td>(1)</td>
</tr>
<tr>
<td>Manure</td>
<td>26</td>
<td>2000</td>
<td>(Level 1)</td>
<td>Based on (2)</td>
<td></td>
<td>(2)</td>
</tr>
<tr>
<td>Chemical fertilizer</td>
<td>None</td>
<td>1870</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemical fertilizer on pasture</td>
<td>None</td>
<td>1870-1900</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemical fertilizer on pasture</td>
<td>2</td>
<td>1950</td>
<td>(Level 1)</td>
<td>Assumption of same amount as in 2000 on pasture</td>
<td></td>
<td>(2),(4)</td>
</tr>
<tr>
<td>Chemical fertilizer on pasture</td>
<td>7.4</td>
<td>2000</td>
<td>(Level 1)</td>
<td></td>
<td></td>
<td>(4)</td>
</tr>
<tr>
<td>Sources: (1) Hoffman 1999; (2) SOS 2003a; (3) Jansson 1988; (4) SOS 2002</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>Amount N in kg/ha</th>
<th>Year</th>
<th>Uncertainty range</th>
<th>Comments</th>
<th>Comments</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deposition</td>
<td>0.95</td>
<td>1870/1900</td>
<td>(Level 3)</td>
<td>Based on calculations from source</td>
<td></td>
<td>(1)</td>
</tr>
<tr>
<td>Deposition</td>
<td>2-2.5</td>
<td>1950</td>
<td>(Level 2)</td>
<td></td>
<td></td>
<td>(1), (6)</td>
</tr>
<tr>
<td>Deposition</td>
<td>9-10</td>
<td>2000</td>
<td>(Level 1)</td>
<td></td>
<td></td>
<td>(2)</td>
</tr>
<tr>
<td>Fixation</td>
<td>10-11</td>
<td>1870-2000</td>
<td>(Level 1-3)</td>
<td>Due to lack of historical information, the value for 2000 was assumed valid for the entire period.</td>
<td></td>
<td>(2)</td>
</tr>
<tr>
<td>Fixation</td>
<td>27</td>
<td>1870</td>
<td>(Level 3)</td>
<td>Average value</td>
<td></td>
<td>(1)</td>
</tr>
<tr>
<td>Fixation</td>
<td>23</td>
<td>1900</td>
<td>(Level 3)</td>
<td>Average value</td>
<td></td>
<td>(1)</td>
</tr>
<tr>
<td>Fixation</td>
<td>23</td>
<td>1950</td>
<td>(Level 2)</td>
<td>Average value</td>
<td></td>
<td>(1)</td>
</tr>
<tr>
<td>Fixation</td>
<td>23</td>
<td>2000</td>
<td>(Level 1)</td>
<td></td>
<td></td>
<td>(2)</td>
</tr>
<tr>
<td>Leakage from arable land</td>
<td>1-11</td>
<td>1870-2000</td>
<td>(Level 2)</td>
<td></td>
<td></td>
<td>(1)</td>
</tr>
<tr>
<td>Leakage from pasture</td>
<td>6.9</td>
<td>1870</td>
<td>(Level 3)</td>
<td>Assumed was the same share of emissions from chem fert and manure as in 2000</td>
<td></td>
<td>(1), (2), (3)</td>
</tr>
<tr>
<td>Leakage from pasture</td>
<td>7.1</td>
<td>1900</td>
<td>(Level 3)</td>
<td>See above</td>
<td></td>
<td>(1), (2), (3)</td>
</tr>
<tr>
<td>Leakage from pasture</td>
<td>8.2</td>
<td>1950</td>
<td>(Level 2)</td>
<td>See above</td>
<td></td>
<td>(1), (2), (3)</td>
</tr>
<tr>
<td>Leakage from pasture</td>
<td>16</td>
<td>2000</td>
<td>(Level 2)</td>
<td>Calculations based on (2),(3),(4)</td>
<td></td>
<td>(2), (3), (4)</td>
</tr>
<tr>
<td>Leakage from pasture</td>
<td>2.1</td>
<td>1870</td>
<td>(Level 3)</td>
<td>Assumption same share of emission per manure/ chem fert as in 2000</td>
<td></td>
<td>(3), (4)</td>
</tr>
<tr>
<td>Leakage from pasture</td>
<td>2.1</td>
<td>1900</td>
<td>(Level 3)</td>
<td>See above</td>
<td></td>
<td>(3), (4)</td>
</tr>
<tr>
<td>Leakage from pasture</td>
<td>2.15</td>
<td>1950</td>
<td>(Level 2)</td>
<td>See above</td>
<td></td>
<td>(3), (4)</td>
</tr>
<tr>
<td>Leakage from pasture</td>
<td>2.9</td>
<td>2000</td>
<td>(Level 2)</td>
<td>Sum of all emissions</td>
<td></td>
<td>(3), (4)</td>
</tr>
<tr>
<td>Ammonia-N from manure</td>
<td>1870-2000</td>
<td>(Level 3)</td>
<td>20% of tot N in manure</td>
<td>Based on (3), (4), (5)</td>
<td></td>
<td>(3), (4), (5)</td>
</tr>
</tbody>
</table>

Sources: (1) Hoffman 1999; (2) SOS 2003a; (3) SOS 2003b; (4) Nielsen et al 1992; (5) Naturvårdsverket 1997f;
<table>
<thead>
<tr>
<th>Fertilizer</th>
<th>Amount P in kg/ha</th>
<th>Year</th>
<th>Uncertainty range</th>
<th>Comments</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manure from grazing</td>
<td>2</td>
<td>1870-2000</td>
<td>(Level 1-3)</td>
<td>Assumption that 2000 data is valid for the entire period, due to lack of more specific data</td>
<td>(2)</td>
</tr>
<tr>
<td>Manure</td>
<td>3.7</td>
<td>1870</td>
<td>(Level 3)</td>
<td>Assumption that N/P share is equal at all times.</td>
<td>(1)</td>
</tr>
<tr>
<td></td>
<td>3.8</td>
<td>1900</td>
<td>(Level 3)</td>
<td>Assumption that N/P share is equal at all times.</td>
<td>(1)</td>
</tr>
<tr>
<td></td>
<td>4.3</td>
<td>1950</td>
<td>(Level 2)</td>
<td>Assumption that N/P share is equal at all times.</td>
<td>(1)</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>2000</td>
<td>(Level 1)</td>
<td></td>
<td>(2)</td>
</tr>
<tr>
<td>Chemical fertilizer</td>
<td>None</td>
<td>1870</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1900</td>
<td>(Level 3)</td>
<td>In 1900 4 kg/ha acc to (4) (mostly south of Sweden), 25% of this was assumed to be valid in Östergötland.</td>
<td>(4)</td>
</tr>
<tr>
<td></td>
<td>2.25</td>
<td>1950</td>
<td>(Level 3)</td>
<td>(5): 9 kg/ha (25%, see above)</td>
<td>(4)</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>2000</td>
<td>(Level 1)</td>
<td>Based on (2)</td>
<td>(2)</td>
</tr>
<tr>
<td>Chemical fertilizer on pasture</td>
<td>None</td>
<td>1870-1900</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.39</td>
<td>1950</td>
<td>(Level 3)</td>
<td>Only on some share of pasture, assumption, equal share at 2000</td>
<td>(5), (6)</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>2000</td>
<td>(Level 1)</td>
<td></td>
<td>(5), (6)</td>
</tr>
<tr>
<td>Deposition</td>
<td>0.3</td>
<td>1870-2000</td>
<td>(Level 3)</td>
<td>Value for 2000 is assumed to be valid for the entire period, due to lack of more precise historical data</td>
<td>(2)</td>
</tr>
<tr>
<td>Leakage from arable land</td>
<td>0.0-0.3</td>
<td>1870-1900</td>
<td></td>
<td>Assumed value</td>
<td>(2), (3)</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>1950</td>
<td>(Level 2)</td>
<td>Assumed to be equal to 2000 – lack of more precise data</td>
<td>(2), (3)</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>2000</td>
<td>(Level 1)</td>
<td></td>
<td>(2), (3)</td>
</tr>
<tr>
<td>Leakage from pasture</td>
<td>0.0-0.2</td>
<td>1870-2000</td>
<td></td>
<td>Assumption – no data available</td>
<td></td>
</tr>
</tbody>
</table>

Sources: (1) Hoffman 1999; (2) SOS 2003a; (3) Naturvårdsverket 1997d; (4) Jansson 1988; (5) SOS 2002; (6) SCB and SJV 2003
Food production in system I:
The process of animal production includes all animal products, i.e. meat, fish, egg and dairy products. The process of plant production includes all vegetable products, i.e. cereals, potatoes, vegetables, fruits, sugar. Dairy products are all calculated in average milk equivalents, i.e. factor 10 for cheese and factor 12.5 for butter. Amounts of N and P in plant products were obtained from SLV 1990 and SJV 2003b and assumed to be valid for the entire period.

Yield per hectare:
For 1870 and 1900 data for vegetables was, due to lack of more precise data, calculated on an average of legumes, peas and root crops, and for fruits, data was calculated on an average for apples, pears and plums obtained from Hö 1869-1951 and SOS 1959, for 1950 and 2000 all were calculated in relation to the average consumption based on SJV 2003a; SCB and SJV 2003 and SCB 2001. For sugar from sugar beet, the modern processing ratio of 1:6.5 (Carlsson-Kanyama and Faist 2000) was assumed to be valid for the entire period. Seeds are assumed to be produced and used within the process of plant production. Harvest losses are included in the calculation of the spatial imprint, by assumed 10-20% for 1870 and 1900 and 3% for 1950 and 2000, in system I, harvest losses were assumed to be left on the fields and hence not added to the harvest. Range of the input data in round figures is presented below. For sugar beet (all years), potatoes (1950; 2000) and cereals, potatoes, vegetables (2000), an assumed uncertainty range is given in exact numbers. Average data is shown in figure 3.1.
1870: cereals 1 230 - 1 800 kg/hectare; potatoes 6 390 - 7 980 kg/hectare; vegetables 1 610 – 12 230 kg/hectare; fruit no data available - assumption 1 000 - 2 000 kg/hectare; sugar beet 9 450 - 11 550 kg/hectare
1900: cereals 1 410 – 1 730 kg/hectare; potatoes 7 630 – 9 330 kg/hectare; vegetables 1 310 – 18 300 kg/hectare; fruit no data available - assumption 1 000 – 4 000 kg/hectare; sugar beet 22 950 – 28 050 kg/hectare
1950: cereals 2 250 - 2 750 kg/hectare, potatoes 10 980 - 13 420 kg/hectare; vegetables 1 640 - 23 000 kg/hectare; fruit 6 660 – 15 370 kg/hectare; sugar beet 33 330 - 37 070 kg/hectare
2000: cereals 4 950 – 6 050 kg/hectare; potatoes 26 540 - 32 440; vegetables 32 000 - 48 000; fruits 7 420 – 19 710 kg/hectare; sugar beet 42 210 - 51 590 kg/hectare

Table D7: Share of N and P in foods:

<table>
<thead>
<tr>
<th></th>
<th>Milk</th>
<th>Cereals</th>
<th>Fats</th>
<th>Meat</th>
<th>Fish</th>
<th>Egg</th>
<th>Vegetables</th>
<th>Fruits</th>
<th>Potatoes</th>
<th>Sugar</th>
</tr>
</thead>
<tbody>
<tr>
<td>g N/kg</td>
<td>4.7</td>
<td>11.7</td>
<td>-</td>
<td>31-42</td>
<td>29</td>
<td>20</td>
<td>4.2</td>
<td>1.92</td>
<td>2.7</td>
<td>0.0025</td>
</tr>
<tr>
<td>g P/kg</td>
<td>0.9</td>
<td>1.6</td>
<td>0.1</td>
<td>1.8-1.9</td>
<td>2.1</td>
<td>2</td>
<td>0.43</td>
<td>0.3</td>
<td>0.46</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Average based on SLV 1990 (round figures)
Food consumption:
The food groups consist of several different foods. Milk includes all dairy products except fats. In some cases the consumption of cheese was also specified. Fats were divided into fats on animal or vegetable base. Meat was divided into beef, pork and poultry. Vegetables included all legumes, vegetables, root crops etc except potatoes. Rice is included in the amount of cereals (and accounts for 6% of the total) and calculated as cereal production, since no rice can be produced in Sweden. Fruits included fruits, berries and nuts. Categories were mainly adapted to the national food statistics (SJV 2003a). Due to the assumed regional production in this study, exotic fruits such as bananas were replaced with local fruits in the calculations. Beverages were included according to the national food statistics, however alcoholic beverages and coffee were not taken into consideration.

The results given in Paper I were varied slightly for the use in paper II to V. For the consumption of milk (which was considered a convalescent diet) and cheese, the average given in Juréen (cited in Morell 1989) was used, since the hospital diet was assumed to exaggerate the intake of these two food products. The consumption data was as followed: 144 kg milk per capita and 1.8 kg cheese per capita in 1870 and 199 kg milk per capita and 2.4 kg cheese per capita in 1900. For the consumption of meat, an average was calculated from the consumption given in Paper I and Juréen (cited in Morell 1989); 39 kg meat per capita in 1870 and 43 kg meat per capita in 1900. Data in 1870-1940 are level 2, data from 1950 to 2000 are level 1.

Scenario of a lacto-ovo vegetarian diet (no meat or fish; applied in chapter 6)
The data is an estimation, based on the average diet for the year 2000 and gives the following composition:
meat 0%; fish 0%; egg 2%; dairy prod (milk equiv) 49%; cereals 11%; vegetables 10%; potatoes 11%; fruit 13% and sugar 4%.  

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