Flows of nitrogen and phosphorus in municipal waste: a substance flow analysis in Finland

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Abstract: Nitrogen (N) and phosphorus (P) are two nutrients contributing to several environmental problems, particularly eutrophication of surface waters. Leakages of these nutrients occur through human activity. In this study, the flows of N and P in the Finnish municipal waste system in 1952–1999 were determined and analysed using substance flow analysis (SFA). Nutrient flows in both wastewaters and solid waste peaked in 1990, after which they declined until 1994 but thereafter increased again although remaining lower than in 1990. At the end of the 1990s the wastewater and solid waste from municipalities and rural households contained ca. 7.0 kg N person^{-1} a^{-1} and 1.1 kg P person^{-1} a^{-1}. Untreated wastewater contained three times more N and four times more P than solid waste. The amounts of N and P involved in recycling increased over the study period being 10% for N and 50% for P at the end of the 1990s.

Keywords: nitrogen; phosphorus; municipal wastewater; municipal solid waste; substance flow analysis; time series; Finland.

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1 Introduction

Population increase and human activity have accelerated and increased the cycling of nitrogen (N) and phosphorus (P) in the environment during the past hundred years [1–3]. As a result, emissions of N and P have grown contributing to various environmental problems, such as eutrophication of surface waters [4]. Emissions of N to air contribute to acidification (release of ammonia, NH_3, and nitrogen oxides, NO_X) and climate change (release of nitrous oxide, N_2O) [5]. Multiple problems related to nutrient use have evoked calls for more efficient and holistic nutrient management [5,6].

Leaks of N and P occur from the human consumption system in the form of wastewaters and solid waste, but detailed descriptions of their flows to, through and from the waste management systems have been rare and often simple input-output balances [7]. The flow of P from sewage sludge back to the soil in a Swiss region has been assessed by Brunner and Baccini [8]. Eriksson et al. ([9] see also [10]) have developed a computer-based model for calculation of nutrient and other substance flows in waste management systems. To the knowledge of the authors, the only detailed substance flow analysis for waste management has been provided by Bertram et al. [11] who studied copper in the European waste management system.

1.1 Waste system in Finland

Finland has a population of 5.2 million and average population density of 17 inhabitants km^{-2}. The sparse population is reflected in the structure of the Finnish waste management system: avoiding long transportation distances of solid waste has resulted in numerous small landfills throughout the country and, until recently, landfilling was the prevalent method of waste-disposal. Since Finland joined the European Union in 1995, municipal waste management has been subject to both national and EU waste regulations.

Before the 1970s, emphasis on waste management in Finland was on sanitary aspects and connected to the development of general healthcare regulation. The growth of gross domestic product (GDP) and urban population after the Second World War accelerated the production of municipal solid waste. The composition of municipal waste in Finnish cities began to resemble that of other European cities [12]. In the 1950s it became common to build waste furnaces in residential buildings but these were abandoned in the 1970s when odour and small particles due to low combustion temperatures were considered too much of a problem [13]. In the early 1980s waste management was administratively separated from public sanitation, gained impetus and became more and more focused on environmental protection in broad sense.

The construction of a modern sewage system in Helsinki, the capital of Finland, was initiated in 1878. Wastewater treatment in other larger towns was started in the first decades of the 20th century [12]. Although occasional concerns were raised over water pollution, wastewater treatment remained relatively rare until the 1970s [14]. The first treatment efforts concentrated on removing phosphorus. Nitrogen removal became an issue in the 1980s and was gradually introduced into practice in the 1990s [15].

1.2 Objective

For a long time environmental protection was focused on point source control of emissions. More recently integrated pollution prevention and control (IPPC) has become a primary principle of environmental protection policies. According to IPPC, resource use and emissions to water, air and soil are controlled and reduced simultaneously. Holistic studies concentrating on all the inflows and outflows of the substances under study in a certain system provide means to identify effective policy options and reduce the risk of simply shifting pollution from one environmental media to another. Studies over long periods of time give information on the evolution of systems towards more or less sustainable use of resources. In addition, stock-building and potential future sources of emissions can be spotted.

The objective of this study was to quantify and analyse over time and rank by source the flows of N and P in the municipal and rural household wastewater and solid waste in Finland. Moreover the purpose was to find possibilities to reduce the hazardous emissions of nutrients, particularly emissions to waters, and to increase nutrient recovery. Previous studies on nutrient flows mainly study the human production and consumption system as a whole [7,8,16–18]. To the knowledge of the authors, there are no prior comprehensive long-term studies on flows of N and P in municipal waste. Yet quantification of nutrient flows in the waste management system is essential in order to determine the final fate of nutrients and to identify main leakages from the human consumption system. It also offers means to detect suboptimal waste management practices, such as landfilling of materials that would still have recovery potential [11].

The period under study extended from 1952 to 1999 for wastewaters and from 1960 to 1999 for solid waste. Between 1960 and 1990, the annual nutrient flows associated with municipal solid waste were determined in five-year intervals due to data availability reasons. Changes over time in the disposal of N and P as municipal waste were analysed. Each year in the period 1995–1999 was recorded and an average was calculated. A detailed flow diagram of the municipal waste management system for the period 1995–1999 was constructed. The N and P flows in different parts of the waste system were compared in order to identify the main sources of losses and possibilities to enhance recycling.

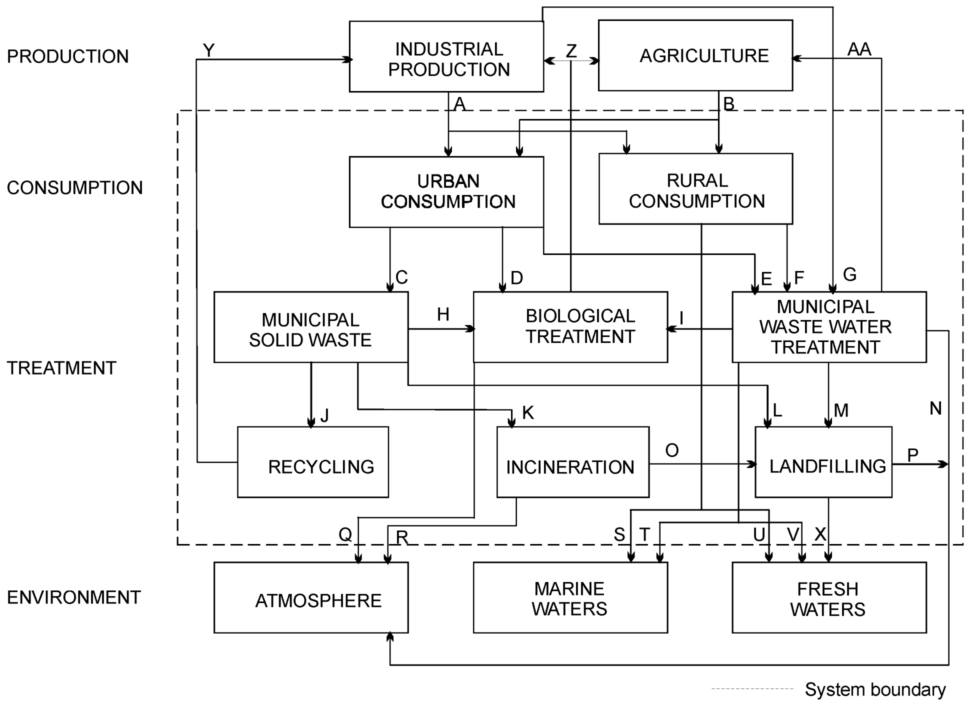
2 Materials and methods

The main research method used was substance flow analysis, SFA (see e.g. [19]). In SFA, the flows of one or a limited group of chemically defined substances within a pre-specified geographical region are determined. The aim is to find out the most important emissions and emission sources for the substance under study. SFA is a sub-term of material flow analysis (MFA), which is a framework covering all the techniques aimed at human societies' materials accounting [20]. While SFA concentrates on one or few substances, MFA analyses all the material flows related to a city or a country. MFA and SFA enable policy makers to trace the origin of pollution problems and to assess management practices. Moreover the methods can be used to find possibilities for amending or preventing pollution problems [21].

2.1 System definition

The whole system under study, containing municipal and rural wastewaters and municipal solid waste, is referred to as the municipal waste system (Figure 1). The shoreline of Finland (including the shore of inland waters) and the land-atmosphere interface constitute the system boundary. The analysis only considers total N and P, not their different compounds. Municipal sewage sludges (*I, M* and *AA* [22]), which originate from municipal wastewater treatment, form an important part of the system. The term municipal solid waste (*C*) refers to all the miscellaneous waste, such as kitchen waste, yard trimmings, waste paper and packaging that are treated in the municipal waste management system. In addition to households, municipal solid waste originates from small industries and businesses and public and private institutions.

Figure 1 Flows of nitrogen and phosphorus considered



A: Industrial products to consumption; B: Agricultural products to consumption; C: Municipal solid waste; D: Biological treatment of household waste at source; E: Municipal wastewater; F: Sediment basin sludge; G: Industrial wastewater and wastewater treatment chemicals; H: Biological treatment of municipal solid waste; I: Biological treatment of sewage sludge; J: Separately collected recycling paper; K: Incineration of solid waste; L: Landfill deposition of solid waste; M: Landfill deposition of sewage sludge; N: Emissions to air from wastewater treatment (incl. anaerobic stabilisation of sewage sludge); O: Landfill deposition of incineration ashes; P: Emissions to air from landfill deposition; Q: Emissions to air from biological treatment R: Emissions to air from incineration; S, U: Rural household wastewater discharges; T, V: Municipal wastewater discharges; X: Leaching from landfills; Y: Recovery of recycled paper; Z: Utilisation of biologically treated municipal waste (incl. sewage sludge); AA: Utilisation of sewage sludge;

Nutrients enter the municipal waste management system through private consumption of products from the industrial and agricultural sectors (*A to G* in Figure 1). In this study, these nutrients are considered as inputs to the system. Once in the municipal waste management system, nutrients may be treated in one of the four different pathways: recycling (*J*), biological treatment (i.e. composting and anaerobic treatment) (*D, H* and *I*), incineration (*K*) or landfill deposition (*L, M* and *O*). Some of the material may also be returned to production (*Y, Z* and *AA*). Loss of nutrients from the waste management system into the environment can occur either through aqueous emissions from municipal wastewater treatment plants (*T, V*) wastewaters from rural areas (*S* and *U*), landfill leachates (*X*) and leaching from compost fields (not assessed in this study due to low data availability) or through gaseous emissions from biological treatment (*N),* wastewater treatment (*Q*), incineration (*R*) and landfills (*P*). In this study nutrient emissions to waters and air and recycled nutrients (*Y, Z* and *AA*) were examined as outputs from the municipal waste management system. In the surveyed time period, landfills were considered as sinks of nutrients [23,24].

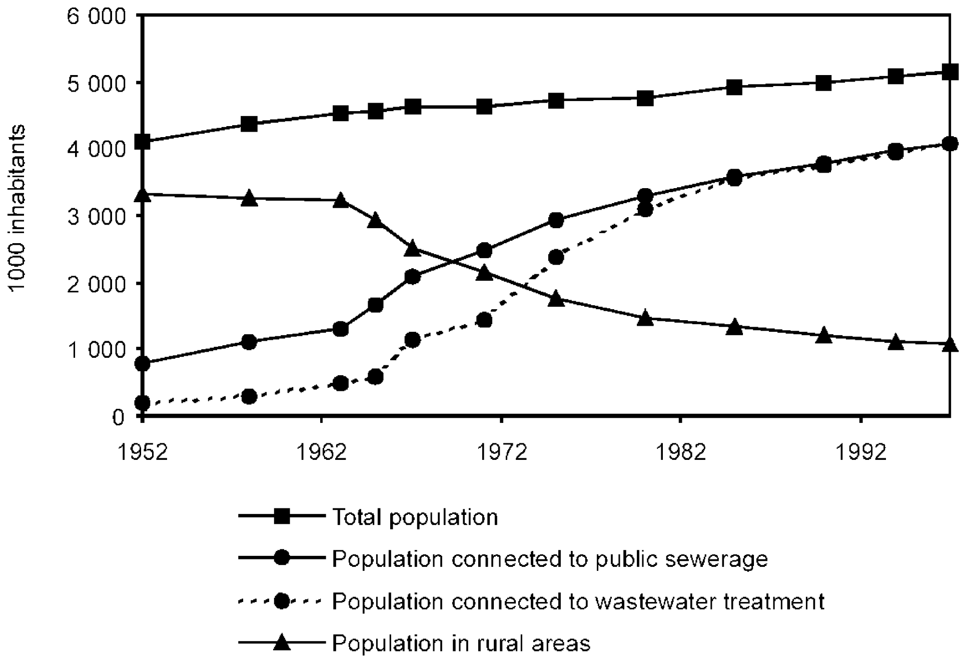
2.2 Nutrient flows in municipal and rural household wastewaters

Untreated household wastewaters originate from both urban and rural areas (*E, F, S* and *U*) (Figure 2). Annual N and P flows associated with untreated household wastewaters (HWW) were estimated using equation (1).

$$\mathrm{HWW}_{\mathrm{N,P}} = \text{population} \times \text{nutrient load per capita}_{\mathrm{N,P}} \tag{1}$$

where the nutrient load for the period 1952–1967 was estimated to be 4.4 kg N $\text{person}^{-1}\,\text{a}^{-1}$ and 0.7 kg P $\text{person}^{-1}\,\text{a}^{-1}$ [25]. The studied years were chosen for data availability reasons.

Figure 2 Penetration of wastewater treatment in Finland in 1952–1997



Data on nutrient content of the total municipal wastewaters (*E* to *G*) entering treatment plants between 1971–1990 were received from Lapinlampi and Raassina [15]. Data for years 1994–1999 were received from the environmental emission monitoring data [26], which are based on legislation about the reporting and control of N and P. Since part of the municipal wastewaters stem from industries (WWI), equation (2) was used to separate those from household wastewaters.

$$WWI_{N,P} = \text{Total nutrient load}_{N,P} \text{ in untreated wastewater entering treatment plants} - \text{population connected to treatment plants} \times \text{nutrient load per capita}_{N,P} \quad (2)$$

where the nutrient load per capita was 5.1 kg N $person^{-1}$ a^{-1} and 0.8 kg P a^{-1} $year^{-1}$, respectively [27]. Data on the nutrients discharged from municipal wastewater treatment plants to water-courses (*T* and *V*) were based on the emission monitoring data [26].

We considered 20% of the total N in wastewater to be bound to the sludge by microbial action in the wastewater treatment plants during the N removal process and the rest of the removed nitrogen to volatilise in the air as gaseous nitrogen (*N*) [28]. Phosphorus in sewage sludge was calculated by deducting the P discharge to waters from the total P content of the untreated wastewater. Sewage sludge disposal was estimated separately for agricultural use (*AA*), landscaping (*Z*) and landfill deposition (*M*) [15].

The nutrient load per capita of 5.1 kg N $person^{-1}$ a^{-1} and 0.8 kg P $person^{-1}$ a^{-1} were used to calculate the total nutrient load in rural household wastewaters during the period 1971–1997 (as an average of 1995–1999) (equation (2)). The discharge of nutrients to watercourses from rural areas (*S* and *U*) could not be reliably assessed before 1990s. The discharge of nutrients from rural areas in 1990 and in 1994 was estimated from Marttunen [29] and in 1997 as reported in the Statistical Yearbook of Finland [30]. Since there is no information available on the discharge of nutrients separately to freshwaters and marine waters, we have considered that 90% of the rural wastewaters are discharged in freshwaters on the basis of the ratio between marine and freshwater shoreline in Finland (*S* and *U*).

2.3 *Nutrient flows in municipal solid waste*

The amount and partitioning of N and P in municipal solid waste (*C* and *D*) was determined with equation (3).

$$MSW = MSW_i \times \text{concentration}_{N,P} \quad (3)$$

where MSW represents municipal solid waste and i the percentage of waste component (organic waste, paper and cardboard, textile and plastic). Estimations on solid waste generation and composition were based on the literature (Table 1).

Table 1 References used as the basis for estimating the production, composition and disposal of municipal solid waste

Years	*Municipal solid waste production*	*Municipal solid waste composition*	*Municipal solid waste disposal*
1960–1970	[31–33] (Approximated from year 1975, assuming an annual growth rate 4%)	[31,33,34]	[33,35–37]
1975	[33,35]		
1980	[36,38]	[36,39]	
1985	[40]		
1990	[41]	[41]	[41]
1994	[42]	[42]	[35,43]
1995–1999	[44–47]	[44–46]	[43,48,49]

N and P contents were determined for organic waste, paper and cardboard, textile and plastic waste (only N). Definitions for textile waste vary, sometimes including rubber, leather and diapers. Calculations of the N and P contents of different waste components were based on various national and international data sources (Table 2). The dry matter content of organic waste was assumed to be 35% [50,52]. Estimations for the other waste components were based on fresh weight and mean values derived of maximum and minimum concentrations whenever such values where available.

Table 2 Nutrient concentration (%) of different municipal solid waste components

Waste fraction	*N content (range)*	*P content (range)*
Organic waste	2 (1.3–2.7) [50–53]	0.4 (0.26–0.5) [50–53]
Paper and cardboard	0.15 (0–0.3) [24,53–55]	0.024 [56]
Textile waste	3.7 (2.9–4.5) [24,53,54,57]*	0.014*
Plastic	0.45 (0–0.9) [53,54,57]	NA

*Own estimation

NA = Not Applicable.

Partitioning between the four solid waste treatment categories (recycling (*J*), biological treatment (*D* and *H)*, incineration (*K*) and landfilling (*L*)) was carried out by deducting the incinerated, recycled, or otherwise recovered waste amount from the total municipal solid waste amount (*C* and *D*) (Table 1). A more detailed analysis of the fate of nitrogen and phosphorus was carried out for the period 1995–1999. Since the most reliable figures on the municipal waste treatment are only available from 1997 onwards, instead of calculating an average of 1995–1999, the value for 1997 was chosen to represent the whole period.

The annual rate of landfill leachate generation (*X*) was estimated to be $27\,\mathrm{l\,t^{-1}}$ waste [58] and the average N and P contents of the leachate $100\,\mathrm{mg\,N\,l^{-1}}$ and $0.8\,\mathrm{mg\,P\,l^{-1}}$ [59]. Total landfill gas generation (*P*) was estimated to be $5\,\mathrm{m^3\,t^{-1}\,year^{-1}}$ and the total N content of the gas was assumed to be 3.5% [60]. Energy recovery of landfill gas was not assessed in this study. Nitrogen emissions to air from biological treatment (*Q*) were estimated to be 50% of the total nitrogen content of the compost or sludge [61,62]. All phosphorus was assumed to remain in the treatment residue and be used in agricultural production or landscaping. In 1997 about half of all sewage sludge was stabilised anaerobically. The annual biogas production in wastewater treatment plants was approximately 22.8 million $\mathrm{m^3}$ [63] and its N content was assessed to be 3.5% [60].

All P was assumed to stay in the ashes after incineration (*O*). If the incineration process works properly, practically all N in waste is emitted in the air during combustion (*R*). Thus incineration ashes were assumed to be N-free. The quality of the released nitrogen was not assessed in this study.

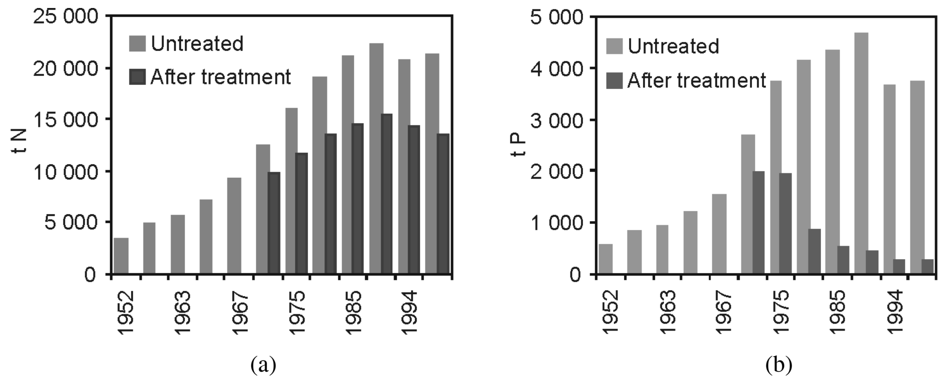
3 Results

3.1 Changing flows of nitrogen and phosphorus in wastewaters

3.1.1 Municipal wastewaters

The annual flow of N and P in untreated municipal wastewaters (*E* to *G*) first increased more than six fold between 1952 and 1990 but then decreased between 1990 and 1994, N by approximately 5% and P by approximately 20%. In 1995–1999, total amount of nutrients in municipal wastewater was again slightly larger than in 1994. Between 1971 and 1997 (an average of 1995–1999) the efficiency of nutrient removal improved steadily, particularly for P. In 1971, only 26% of wastewater P was removed whereas in the 1990s phosphorus removal efficiency exceeded 90%. Nitrogen removal did not improve as much. In 1971 and during 1995–1999, the efficiency of N removal was 21% and 36%, respectively (Figures 3(a) and 3(b)).

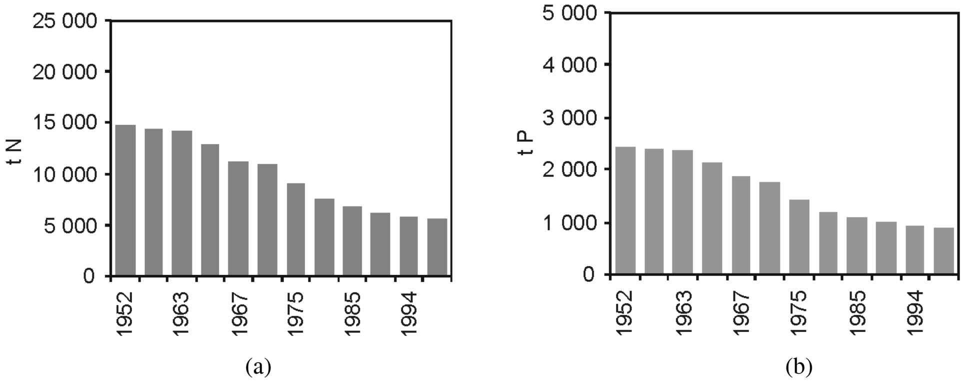
Figure 3 (a) Nitrogen flow in municipal wastewaters in 1952–1997 (*E–G*), (b) Phosphorus flow in municipal wastewaters in 1952–1997 (*E–G*)



3.2 Rural wastewaters

The amount of nutrients in rural household wastewaters (*F, S* and *U*) decreased throughout the study period (Figures 4(a) and 4(b)). During the 1990s, the nutrient discharge of rural household wastewaters was about half of the total nutrient flow in rural wastewaters. Nutrient discharges from rural areas before the 1990s were not assessed in this study, but they can be assumed to have been more than 50% (due to less wide-spread and efficient treatment techniques) but less than 100% of the amount of nutrients in untreated wastewaters (*A*, *B*). Wastewaters were hardly anywhere discharged directly into surface waters and part of the N and P was removed by natural processes, such as filtration.

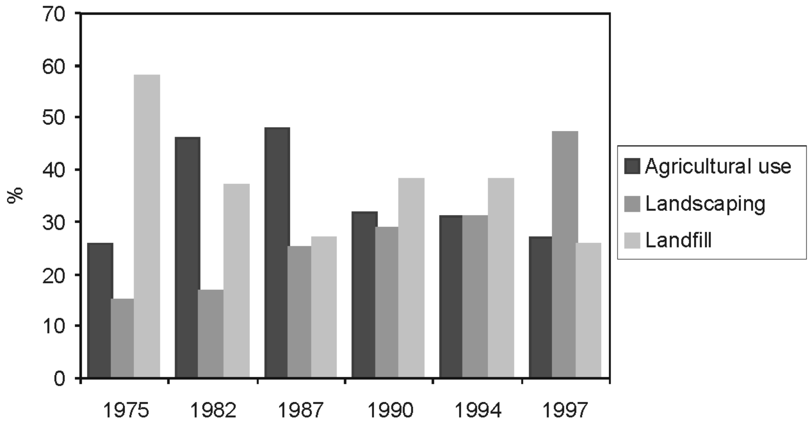
Figure 4 (a) Nitrogen flow in rural household wastewaters in 1952–1997 (*A*, *B*), (b) Phosphorus flow in rural household wastewaters in 1952–1997 (*A*, *B*)



3.2.1 Production and disposal of sewage sludge

The amount of sewage sludge produced doubled between 1975 and 1997. 72,000 t of sewage sludge a^{-1} were produced in 1975, 153,000 t a^{-1} in 1987 and in 1995–1999 an average of 145,000 t a^{-1}. The utilisation of sewage sludge (*I, M* and *AA*) has undergone major changes during the past three decades (Figure 5). In 1975 only about 25% of sewage sludge was used in agriculture. Agricultural use of sewage sludge became common in the 1980s, reaching a peak in 1987 when almost half of the sewage sludge was utilised in agriculture. Agricultural use then declined while the share used in landscaping increased to 47% in 1997 (average of 1995–1999) being thus the most common utilisation method of sewage sludge. Simultaneously, the share of landfill deposition of sewage sludge decreased from 58% (42,000 t) in 1975 to 26% (37,000 t) in 1997 (average of 1995–1999). Incineration as a method for disposing of sewage sludge has, so far, not been used in Finland.

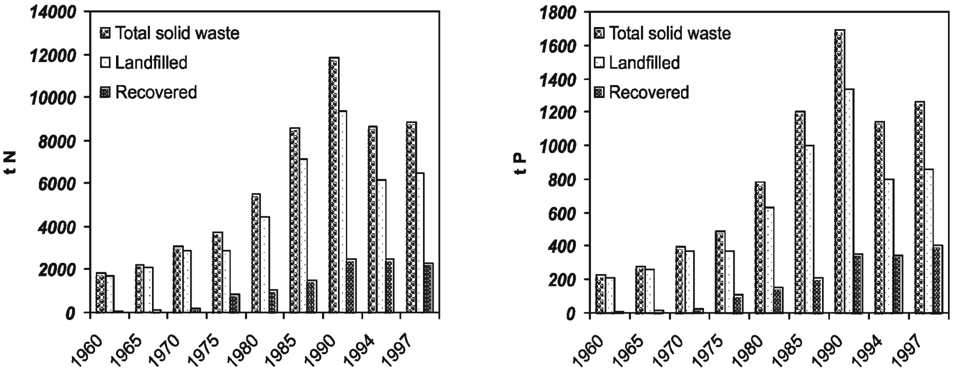
Figure 5 The relative share of different sewage sludge disposal methods in 1975–1997



3.3 Nitrogen and phosphorus in municipal solid waste

The flows of N and P associated with municipal solid waste (*C* and *D*) grew until 1990 (Figure 6(a) and (b)) paralleling the development in total municipal solid waste amounts, which also increased continuously until 1990. Another underlying factor was the constant increase in the share of the organic waste component, which contained most of the nutrients. Growth in the generation of municipal solid waste was particularly fast during the 1980s when the amount of both N and P in municipal solid waste doubled. The share of landfill disposal decreased rather constantly from ca. 95% in the 1960s to ca. 70% in the 1990s. Altogether a total of about 230,000 t N and 30,000 t P was released in municipal solid waste between 1960–1999. Of this approximately 80% were deposited in landfills (*L*).

Figure 6 a) Nitrogen flow in municipal solid waste 1960–1997 (C, D), b) Phosphorus flow in municipal solid waste 1960-1997 (C, D). Recovery refers to incineration, recycling and biological treatment



(a) (b)

3.4 Nitrogen and phosphorus cycle for 1995–1999

3.4.1 N and P flows associated with municipal wastewaters and solid waste

A more detailed analysis of N and P flows in the municipal waste system was conducted for the period 1995–1999 (Figures 7 and 8). According to this analysis, most of the nutrients entering municipal waste system, 26,900 t N a^{-1} and 4,500 t P a^{-1}, were associated with wastewater. Most of these nutrients (ca. 76%) stemmed from households connected to public wastewater treatment plants. 5,800 t N a^{-1} and 900 t P a^{-1} originated from rural areas [64] and approximately 600 t N a^{-1} and 420 t P a^{-1} from industrial wastewaters, mainly wastewaters from food industries. Due to roundings, mass balance is not quite reached for wastewater treatment in Figures 7 and 8.

Figure 7 The flows of nitrogen in the Finnish municipal waste system as an average of 1995–1999

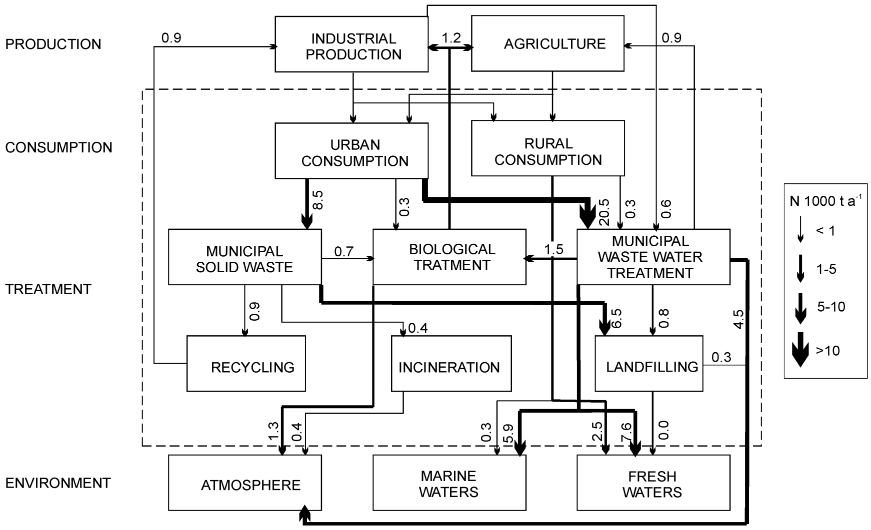
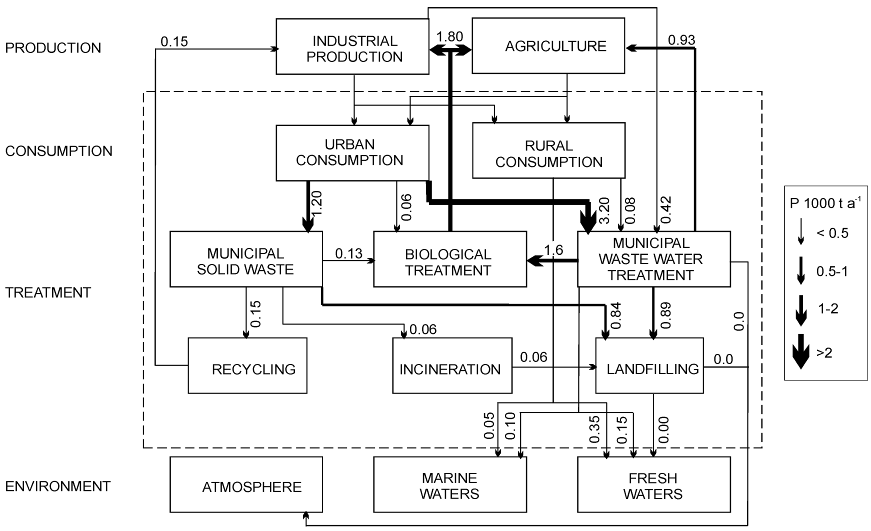


Figure 8 The flows of phosphorus in the Finnish municipal waste system as an average of 1995–1999



Sewage sludge was estimated to contain 3,200 t N a^{-1} and 3,500 t P a^{-1}. Of this approximately 25% were returned to agricultural production. This sludge was either anaerobically digested, lime stabilised or composted. 1,500 t N a^{-1} and 1,600 t P a^{-1} in the sewage sludge were biologically treated and used for landscaping purposes. The rest of the sewage sludge was deposited in landfills. A considerable part of the sewage sludge was anaerobically digested before further treatment or disposal thereby resulting in N emissions to the air (see Section 3.4.2).

Organic waste accounted for ca. 55% of the total annual municipal solid waste N flows and 75% of the annual municipal solid waste P flows. Most of the nutrients in solid waste were deposited in landfills in 1995–1999. Approximately 700 t N year^{-1} and 130 t P year^{-1} in organic waste were separately collected and composted. In addition, a small amount of nutrients in household organic waste were composted at source. Approximately 900 t N a^{-1} and 150 t P a^{-1} were collected separately in paper and recycled in paper manufacturing. Incineration accounted for 400 t N a^{-1} and 60 t P a^{-1}. All of the N was assumed to evaporate in the air while all the P was assumed to be deposited in landfills as incineration ashes.

On average, 7.0 kg N person^{-1} a^{-1} and 1.1 kg P person^{-1} a^{-1} entered the municipal waste management system between 1995 and 1999. Of this about 7,300 t N a^{-1} and 1,790 t P a^{-1}, originating from both solid waste and wastewaters, were deposited in landfills, which act as nutrient sinks during the surveyed time period. Some 3,000 t N a^{-1} and 2,900 t P a^{-1} were returned to production either as sludge to agriculture or as recycled material.

3.4.2 Nutrient emissions to air and water from the municipal waste system

In 1997 (as an average of 1995–1999) wastewater treatment plants discharged 5,900 t N a^{-1} and 100 t P a^{-1} to marine waters and 7,600 t N a^{-1} and 150 t P a^{-1} to freshwaters. P emissions associated with rural household wastewaters were ca. 150 t higher than the P emissions from wastewater treatment plants in 1997. N emissions associated with rural household wastewaters were ca. 2,800 t N a^{-1}. Of the nutrients in rural household wastewater emissions, 10% were estimated to be discharged to marine waters and the rest to freshwaters. Of the total N content of wastewater, 20% were estimated to remain in the sludge. The rest of the removed N was emitted to the air. Nitrogen emissions to the air from anaerobic stabilisation of sewage sludges were estimated to account for further 1,000 t N a^{-1}.

Nitrogen emissions to air during the biological treatment process of both organic waste and sewage sludge were approximately 50% of the total nitrogen content. Some additional N emissions to air were likely to occur from agricultural use of sewage sludge. Leaching from landfills was rather insignificant, being approximately 5 t N a^{-1} and less than 0.05 t P a^{-1}. Leaching from compost fields was not determined in this study. N emissions to air from landfills were estimated to be 300 t N a^{-1}.

4 Discussion

4.1 Changes in the flows of N and P in 1952–1999

Unlike PVC [65] or metals, such as copper [66,67], large quantities of N and P do not reside in the production and consumption system. Most of N and P is contained in food and is thus consumed immediately. Some N and P remain longer in paper, plastics and textile products. However, such materials only contain low N and P concentrations. Therefore significant delayed emissions of N and P from products currently in use are not expected in the future.

The amount of P removed from municipal wastewaters increased considerably throughout the study period, from about 20% in the 1960s to over 90% in the beginning of the 1990s. N removal efficiency did not improve as much; in 1999 it was approximately 44% [15]. This was partly due to the priority given to P control over N control. Most Finnish freshwaters are P limited [29] and thus controlling of P inputs has been considered to be more important than controlling those of N. Moreover, P removal is technically easier and less costly per ton removed than N removal [68,69]. Yet eutrophication of the Baltic Sea is one of the most severe environmental problems facing Finland. The primary production in the Baltic Sea (excl. the Bothnian Bay) is mainly limited by the concentration of available N [68,70,71] and more efficient nitrogen control has therefore been called for.

Total municipal wastewater nutrient flows peaked in 1990 and decreased then from 1990 to 1994. Severe economic recession in the beginning of the 1990s may have reduced the amount of municipal wastewater originating from industries and households during this period. Moreover, a change in the average Finnish diet may have affected the amount of nutrients in wastewaters. For example, per capita protein supply decreased in Finland by a few percent between 1990 and 1994 but has since then increased again [72]. Another important factor affecting the amount of P in wastewaters was the decreased use of P in detergents during the 1990s.

Compared to the municipal wastewater system, the flow of both N and P in the municipal solid waste system is smaller, both in terms of the annual flows and leaching to surface waters. The share of landfilling of nutrients decreased from 95% in the early 1960s to ca. 70% in the 1990s. Yet, due to growth in total municipal solid waste generation, almost four times more N and P were landfilled in 1995–1999 than in 1960. Thus even though recycling of municipal solid waste has become more common, growth in total municipal solid waste amounts seems to be off-setting the achieved benefits. Most of the nutrients in municipal solid waste were contained in the organic waste fraction. Of all the organic solid waste produced, ca. 25% were biologically treated (including composting at source) in 1997. In addition to the high content of N and P, organic waste nutrients are in a form that is most readily reclaimable and also most prone to leaching or volatilisation (N_2). Therefore policies regarding municipal solid waste nutrients should be targeted at the organic waste component.

The leaching of N and P was estimated to be 5 t N a^{-1} and 0.05 t P a^{-1} on average during 1995–1999. Even though this is not a precise estimation, leaching in the short-term can be considered negligible compared to the total N and P contained in the stock of municipal solid waste. This assessment is supported by the studies by Pelkonen et al. [24]. Landfills can therefore be considered relatively stable nutrient storages. Nevertheless there is potential for larger nutrient emissions from landfills in the future as more municipal solid waste has been produced during the past three decades than during the whole previous history. It should also be noted that N and P in landfills are, in any case, lost from the nutrient cycle associated with the human production and consumption system.

4.2 Identifying possibilities to enhance nutrient recycling

According to the results of this study, most of the nutrient flows of the Finnish municipal waste system were associated with wastewaters throughout the study period. The nutrient flows were largely linear i.e. nutrients were not recycled but released in water or air or deposited in landfills. Between 1995–1999 ca. 50% of P and 10% of N in municipal waste were recycled. P losses decreased throughout the study period as P removal from wastewaters improved. The low reutilisation rate of N throughout the study period was mainly due to high levels of emissions. Even though some of the N losses occurred as N_2 emissions to air, all the lost N can be considered a problem in the sense that it is lost from the system and its recapture will require energy.

Since most of the N and P in municipal waste are associated with wastewaters, sewage sludge is important when improving the level of recycling in the municipal waste system. Due to more efficient wastewater treatment and an increasing share of population being connected to wastewater treatment plants, the production of sewage sludge grew throughout the study period. Yet, during the period 1995–1999, sewage sludge contained only about 2.4% of the nitrogen and 11.8% of the phosphorus applied to agricultural soils as synthetic fertilisers during the same time period [73]. Even if all the N and P in sewage sludge was recovered, their importance would be relatively low especially in the case of N. Nevertheless nutrient recycling can only be achieved through integrated activities in all relevant fields. Furthermore, as noted earlier, the best possibility to enhance nutrient recycling in the municipal waste management is in the disposal of sewage sludge.

The quality of Finnish sewage sludge has considerably improved over the past decades due to restrictions on hazardous wastes and the use of chemicals and improvements in other branches of waste management. By the end of the 1990s, most of the municipal sewage sludge fulfilled the criteria set for sludge use in agriculture [74]. Yet potential health hazards and limitations on P application restrict the agricultural use of sewage sludge. In addition, representatives of agriculture have opposed sewage sludge use in agriculture as they consider it a threat to the clean reputation of the Finnish food [74]. Currently the demand for composted organic waste or sewage sludge is low and thus new solutions are needed. For example the quality of sewage sludge could be improved by separating blackwaters (i.e. toilet waste) from greywater (i.e. water used for washing purposes) at source [75].

As most of the nutrients in municipal waste originate from food production, in the short term there are not many realistic possibilities to reduce the total nutrient quantity cycling. Currently policies should focus on more efficient nutrient recycling in order to reduce leakages of nutrients and increase the level of nutrient utilisation within the whole consumption system. Yet it can be argued that in the long term policies regarding nutrients should focus on limiting the consumed amount of nutrients as well. One factor behind the high intake of N and P is excessive meat consumption. Approximately 7 kg of feed N are needed to produce 1 kg edible N in animal products [76]. Globally the combination of modified diets and reduced losses could save enough N to satisfy the demand for N resulting from population growth and the desire of people in low-income countries to eat more animal products [76]. However, since N and P are essential nutrients there is a limit to how much their use can be reduced and therefore recycling warrants its place as the main goal of sustainable nutrient management.

4.3 Uncertainties

The objectives of this study were to estimate and analyse changes in the flows of N and P in the Finnish municipal waste system, to identify the most important sub-flows in the system and to locate main leaks from the system. There are uncertainties involved in all the figures used in this study, particularly with the nutrient contents of different waste components. Furthermore, relatively accurate estimations on municipal solid waste generation and composition can only be found from the 1990s onwards [42,45,46]. Nevertheless, we have sought to minimise the uncertainties of this study by using an extensive range of reference sources and making comparisons between these sources. The use of annual averages over the period 1995–1999 reduces the effect of extreme results. Also the statistics on waste have become more thorough and reliable over time. We consider the figures presented in this study to be of the right order of magnitude and the trends presented reliable. It should be noted that this study dealt with the flows of total N and P. The impact of emissions will depend on the actual chemical composition of the substance and on the receiving environment. These aspects were not considered in this study.

A further issue to be discussed is the matter of systems definition. This study considered the Finnish municipal waste management system. The results would be different if we had chosen to study only one municipality in Finland or, on the other hand, a larger area, such as Europe or the whole world. Generally, the smaller the system, the more outside influence there is like to be, as practically no country, let alone municipality, is self-sufficient. In the present case, limiting the system to Finland can be justified, as there are no imports or exports of municipal waste in Finland. Yet domestic consumption, producer of the waste, is largely influenced by imports and exports. Moreover, the environmental impacts of the nutrient emissions of the Finnish municipal waste management system are far-reaching in the Baltic Sea region.

4.4 Considering prospects to integrate SFA and LCA

SFA studies, such as the present one, can serve to identify important nutrient flows and leakages and to analyse their origins [19]. Historical analysis also enables one to anticipate potential future problems and to detect gradual changes between flows. Moreover SFA can provide useful information for supporting decision making on the sustainable use of natural resources but it also has several limitations. The data requirements of the method are high and it demands interdisciplinary knowledge and understanding. A single SFA is usually not enough for giving specific recommendations [56]. In addition, SFA does not include socio-cultural or economic aspects. There are some efforts underway to include economic considerations in SFA but more research is needed on this field.

SFA could perhaps be combined with life cycle assessment (LCA) in order to increase its applicability. Bouman et al. [21] have compared SFA, LCA and partial economic equilibrium analysis (PEA) and conclude that these methods are rather complementary than contradictory. They suggest that SFA could be used first to estimate whether certain measures could essentially solve the problem. LCA could then be applied to estimate whether particular solutions lead to other, also serious environmental problems. Finally, PEA would be applied to find the most efficient way of implementation. This way economic considerations could be integrated in the analysis. Social and cultural aspects would, however, still go unnoticed.

Van der Voet et al. [77] have developed a methodology which combines material flow data with environmental impact data from the standard LCA databases. The purpose is to prioritise materials on the basis of their contribution to environmental problems. Although the method has been developed for MFA, a similar approach could be applied for SFA as well. Combining environmental impact assessment data with substance flows would address the problem of quantity vs. quality of the flows noted previously in this paper. While more development is still needed, the method appears very promising.

5 Conclusions

Total flows of N and P associated with the municipal waste system increased from 1952 to 1990 but then levelled off or decreased. Most of the N and P in municipal waste was contained in wastewaters. By the end of the 1990s, untreated municipal and rural household wastewaters corresponded to 5.3 kg N person^{-1} a^{-1} and 0.9 kg P person^{-1} a^{-1} and municipal solid waste 1.7 kg N person^{-1} a^{-1} and 0.2 kg P person^{-1} a^{-1}. Throughout the study period, a considerable amount of N and P was deposited in landfills. Currently, landfills are stable storages but they represent a potential risk for higher emissions in the future. The recycling efficiency of municipal waste N and P increased over the course of the past fifty years, but it was still less than 10% for nitrogen in the end of 1990s. Due to the high rate of P removal from wastewaters, 50% of municipal waste P was recycled in 1995–1999.

Improvement in the recovery of nutrients from the municipal waste system should concentrate on the removal of N from wastewater. The best possibilities to increase nutrient recycling exist in sewage sludge utilisation. Thus to enhance nutrient recycling and to replace inorganic fertilisers, sludge utilisation in agricultural production should be promoted. Source segregation of blackwaters would considerably improve sludge quality. There are prospects for the efficiency of nutrient recovery to improve in the future as new legislative requirements, such as the Landfill Directive (1999/31/EC), are set into force. But more research is required to find workable alternatives for waste nutrient utilisation. Nutrients from waste management cannot replace inorganic fertilisers but they can supplement them and help to reduce their use. Perhaps most importantly, enhanced recycling will reduce the environmental problems related to nutrient emissions from municipal waste.

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