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Department of Soil and Water Sciences

DISPOSAL OF SEWAGE SLUDGE:

HEAVY METAL FLUXES IN NORWEGIAN AGRICULTURE

(A report to SFT, State Pollution Control Authoritis of Norway
SFT, Statens forurensningstilsyn Norge)

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Abstract. Heavy metal fluxes in Norwegian agriculture were estimated on the basis of annual sludge production, phosphate fertilization and crop production in the main agricultural areas of Norway. Soil heavy metal input due to atmospheric deposition and output due to leaching were further included using data from different reports.

In most cases, atmospheric deposition was shown to be the most important source for Cd, Pb, Hg, Ni, and Cr while sludge, to be the most important source for Zn and Cu in Norway. Fertilization contributed the least proportion to soil input with respect to all seven heavy metals except for use of certain types of phosphate fertilizers with high cadmium concentrations.

The sources of soil metal input as well as the order of importance were found to be as follows for different elements:

Cd: atmospheric deposition > sludge application > fertilization
Pb: atmospheric deposition
Hg: atmospheric deposition > sludge application
Ni: atmospheric deposition > sludge application > fertilization
Zn: atmospheric deposition > sludge application
Cu: sludge application > atmospheric deposition > fertilization
Cr: atmospheric deposition > sludge application > fertilization.

Based on the average sludge loading rate, 0.10 T DS/ha (the annual sludge production in dry solids per hectare of cultivated agricultural area excluding fields for growing vegetables), plus those due to fertilization and atmospheric deposition, the soil input rates of Cd, Ni and Zn were lower than their output rates due to crop production and leaching, while the soil fluxes of Cu were nearly balanced. The input rates of Pb, Hg and Cr were much higher than their output rates.

When the maximum permissible sludge loading rate, 2 T DS/ha/yr, was used, the lowest maximum number of years permitted for sludge application without exceeding the maximum permissible concentrations of relevant metals in the soil, were found to be associated either with Cu or with Zn in different counties of Norway. The shortest duration for sludge application in Akershus-Oslo limited by Cu and the next shortest, in Vestfold limited by Zn showed clearly that the concentrations of Cu and Zn are the limiting factors determining the use of sludge in agricultural recycling in Norway. Aimed at promoting the correct use of sludge, further reduction of the concentrations of Cu and Zn in relevant sewage treatment systems should be the most important task in the coming future in Norway.

DISPOSAL OF SEWAGE SLUDGE: HEAVY METAL FLUXES IN NORWEGIAN AGRICULTURE

EINAR VIGERUST XIAOFU WU

Development of adequate treatment capacities for hazardous waste has enabled the establishment of desirable sewage treatment systems for each city and community in Norway. In addition to the highly restrictive hygienization standards, great efforts during the last decade have been put on reducing the levels of the harmful substances in the whole cleaning process. The direct use of untreated sludge is prohibited and the sludge management is strictly regulated by legislation. Thus, the pollution from municipal wastes has been to a large extent minimized.

Norway is a country with the highest proportion (approximately, 60%) of sludge disposal in agricultural recycling in Europe. Due to phycological or historical reasons with fears of environmental contaminations, or due to the uncertainty of the real consequence of the waste treatments and particularly that of the sludge landspreading, negative attitudes towards sludge application still exist and the idea of utilizing sludge as a useful resource in agriculture still remains as a common topic for discussion. As the use of sludge in recycling is generally concerned with the accumulation of heavy metal in the soil, it is necessary to provide necessary information on heavy metal fluxes in Norwegian agriculture.

In the present report, input of soil heavy metals due to sludge application, phosphate fertilization and atmospheric deposition and output of soil heavy metals due to plant uptake and leaching are estimated to county levels for the main agricultural areas in Norway.

Heavy metals from sludge

Sludge production and density

Based on the reports from individual treatment plants, the total sludge production in 1993 in Norway is approximately 89,000 tons in dry matter (T DS). The total cultivated area in Norway reported by Statistics Norway (1993) for 1992 is 883,090 hectares (Table 1). As the use of sludge for growing vegetables is prohibited by legislation, the total cultivated area permitted for sludge application will be then 877,150 hectares when the vegetable fields are excluded. Dividing the total sludge production by this area gives a value of 0.10 tons in dry matter per hectare per year (T DS/ha/yr) as the nation's average sludge production density on the basis of cultivated agricultural areas where sludge is allowed to be spread. This value is 20 times lower than the maximum amount of sludge permitted to be annually spread onto the soil (MPs), 2 T DS/ha/yr, according to the regulation (Table 1)

Table 1. Total sludge production and average sludge production density in relation to cultivated agricultural areas in Norway (Aquateam Norway 1994; Statistics Norway 1993; 1994).

Sludge production (T DS)	Cultivated area (ha)	Vegetable area (ha)	Area for use of sludge (ha)	Sludge per unit area* (T DS/ha)	MPs* (T DS/ha)
89,000	883,090	5,940	877,150	0.10	2

**: Sludge per unit area is the sludge production density given as a ratio of the sludge production to the cultivated agricultural area permitted for use of sludge.*
MPs denotes the maximum quantity of sludge permitted to be annually spread to cultivated soils.

Sludge distribution

The total quantity and density of sludge produced in the main agricultural areas of Norway are shown in Figure 1. In comparison, the Akershus-Oslo region produces the largest quantity of sludge, contributing along 36% of total production in the whole country (Figure 1). The magnitude of sludge production in different regions follows the order:

Akershus-Oslo > Buskerud > Østfold > Oppland > Vest-Agder > Hedmark >

> Telemark > Vestfold > Aust-Agder > the other counties.

The distribution pattern of sludge production density (quantity of sludge per unit cultivated area excluding vegetable lands) differs to certain degree from that of sludge production (Figure 1). Because of its relatively small cultivated area, Vest-Agder county has the highest sludge production density, followed by Akershus-Oslo and other counties in the sequence:

Vest-Agder > Akershus-Oslo > Telemark > Buskerud > Østfold= Aust-Agder >

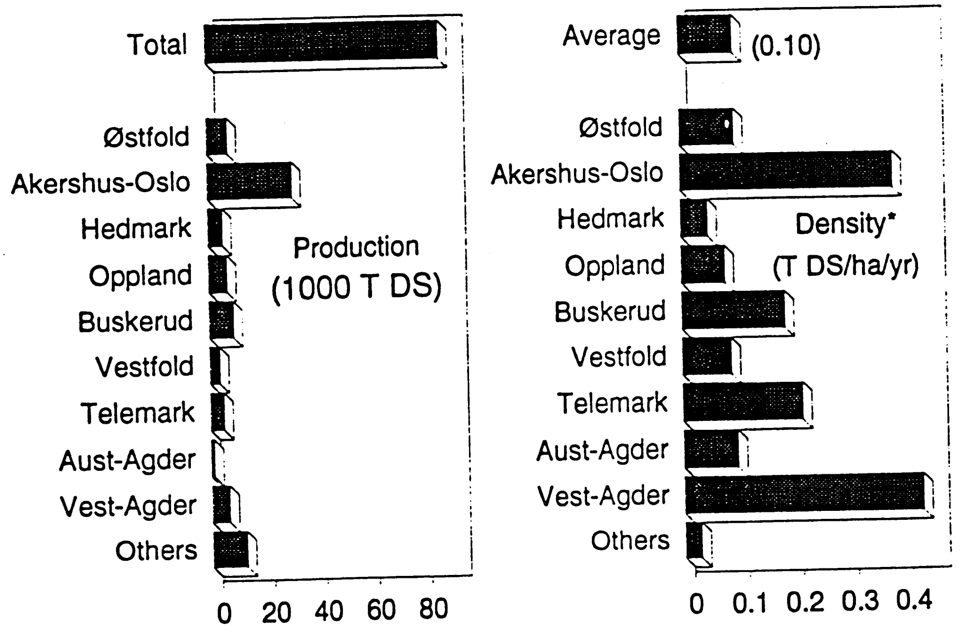
> Vestfold > Oppland > Hedmark > the others.

The sludge production density is a useful index to indicate the potential of sludge disposal in agriculture as it is the maximum average sludge loading rate for a given region if the sludge produced in that region should be locally utilized in agriculture.

Fig. 1. Annual sludge production and distribution in different counties of Norway (Data for 1993).

*: Sludge distribution density given as tons of sludge in dry solid per hectare of cultivated agricultural area excluding fields for growing vegetables.

(Aquateam Norway 1994; Statistics Norway 1993; 1994)



It should be mentioned, however, that the sludge production density can deviate greatly from the actual sludge loading rate. For a given region, the actual sludge loading rate is determined by two factors, the total amount of sludge to be used in agriculture, and the total area to be spread with sludge. In Akershus-Oslo, Hedmark, Oppland and Buskerud regions, sludge has been largely utilized in agricultural recycling and thus the actual loading rate is very high. In most cases, the sludge loading rate is 2 T DS/ha/yr in these areas, i.e., the maximum permissible loading rate is used. On the contrary in Vest-Agder and Aust-agder, use of sludge in agriculture is less common and large proportion of sludge produced in these counties has been dumped into landfills.

Heavy metal concentration and quantity in sludge

The concentrations of all concerned heavy metals in the sludge produced in Norway have been reduced since 1980 due to successful control in the whole sewage treatment process, although the degree of the concentration reduction varies with respect to each individual element (Figure 2). The differences in heavy metal concentrations in the sludge between 1980 and 1991 are significant at higher level for Cd, Pb, Hg, Ni, Zn and Cr ($P < 0.001$) than for Cu ($P < 0.01$) while those between 1991 and 1993, except for Ni, are also significant but at lower levels of significance (Figure 2).

The weighted average concentration of heavy metals in the sludge and the total quantity of heavy metals generated from the sludge produced in 1993 are shown in Figure 3 while those for different counties are given in Table 2. In comparison, the concentrations of Zn and Cu in sludge and also the total quantity of these two metals generated from sludge are approximately 10 to 300 times higher than those of the other metals. The origination of these two metals in sludge are mainly from the pipes leading the sewage to the treatment plants. Increasing the alkalinity of the sewage to decrease the dissolution of Zn and Cu in the system has been discussed as a solution to obtain a significant reduction of the concentrations of these two metals in the sludge.

Annual loading rate of heavy metals from sludge

Similar to the sludge production density, the average loading rate of heavy metals due to sludge application is given as the total quantity of each individual metal divided by the total cultivated agricultural area excluding vegetable lands. The pattern of average loading rate of heavy metals generated from sludge (AAq, Figure 4) is identical to that of the maximum permissible loading rate, given as the product of maximum permissible concentrations of heavy metals in sludge and the maximum quantity of sludge permitted to be spread to the soil, (MPq, Figure 4) according to the regulation. The only difference between these two terms is the scale of the magnitude, namely, AAq is generally 100 times lower than MPq. Similar to the concentrations and quantities of heavy metals in sludge, both the maximum permissible and the average loading rates of Zn and Cu are 10 to 100 times higher than those of the other metals.

Fig. 2. Average concentrations of heavy metals in the sludge produced in different years in Norway (mg/kg DS).

*: significant difference at 0.05 level.
**: significant difference at 0.01 level.
***: significant at 0.001 level.
-: insignificant

(SFT-rapport 93:26 1993; Statistics Norway 1994)

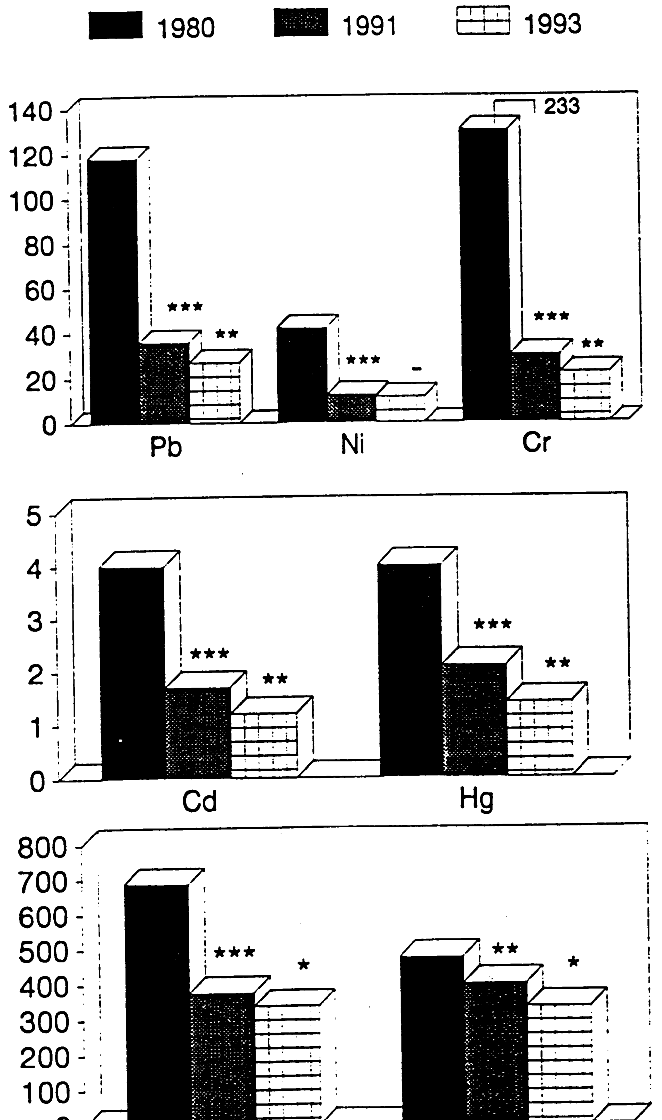


Fig. 3. Weighted average concentrations and total quantity of heavy metals in sludge annually produced in Norway.
(Aquateam Norway 1994; Statistics Norway 1994)

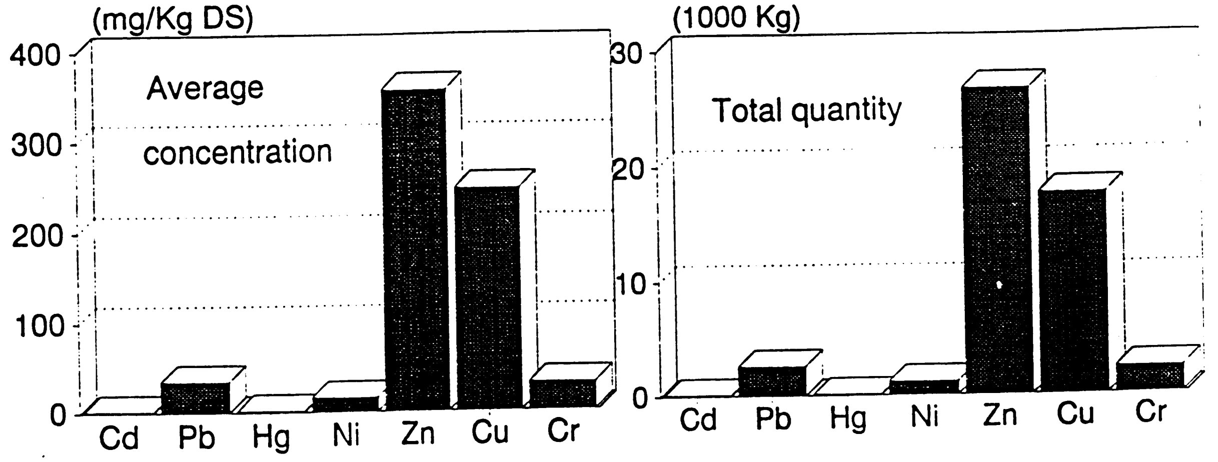
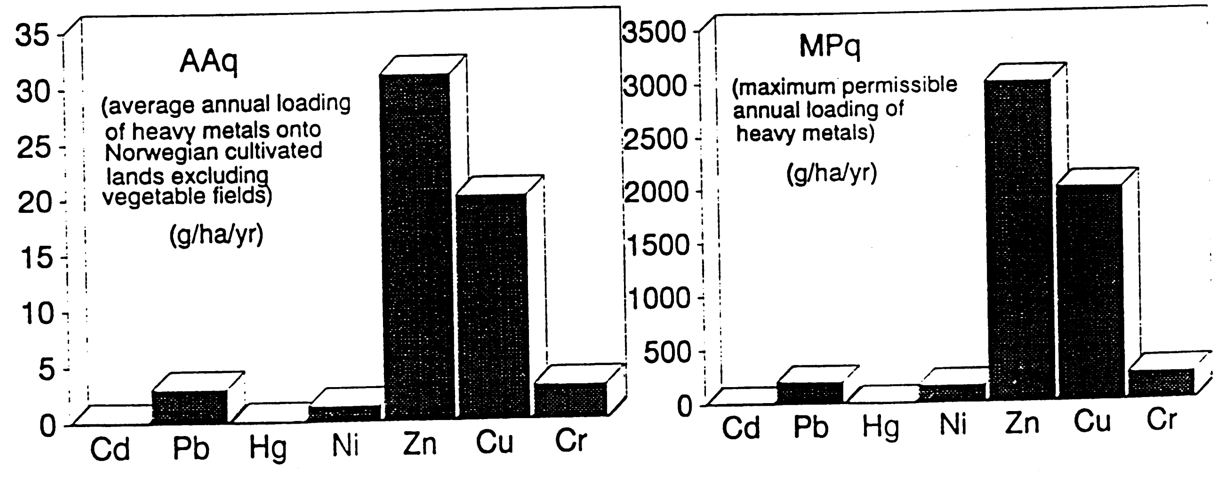


Figure 4. Annual loading rates of heavy metals due to sludge application in Norwegian farmlands.
(Aquateam Norway 1994; Statistics Norway 1994)



The similarity in the shape of the patterns in Figures 3 and 4 indicates high degree of adequacy in Norwegian legislation on setting maximum permissible concentrations of heavy metals in the sludge. The relative values of these limits are highly in accordance with the real heavy metal status in the sludge produced in Norway.

Table 2. Weighted average concentrations of heavy metals in sludge produced in different counties of Norway (based on data from individual treatment plants in different counties) (Aquateam Norway 1994; Statistics Norway 1994) (mg/kg DS)

	Cd	Pb	Hg	Ni	Zn	Cu	Cr
Østfold	1.3	36	1.1	20	402	162	31
Akershu-Oslo	1.7	38	1.6	18	348	310	36
Hedmark	1.8	32	1.7	16	290	216	23
Oppland	1.3	26	2.1	10	308	249	35
Buskerud	0.8	35	1.2	9	391	210	24
Vestfold	0.8	42	1.1	14	519	138	15
Telemark	1.2	40	1.8	22	280	242	53
Aust-Agder	0.9	18	0.8	16	356	247	59
Vest-Agder	1.1	18	1.3	16	363	63	13

Distribution of heavy metals from sludge

The total amount of heavy metals generated from the sludge in Akershus-Oslo region is much higher than that in any of the other counties simply because the Akershus-Oslo region has considerably high quantity of sludge production (Figure 5). The distribution of heavy metal quantity per hectare of cultivated lands excluding vegetable fields shows disparity for different metals in different regions (Figure 6). The order of heavy metal quantity per unit area is as follows:

Cd: Akershus-Oslo > Vest-Agder > Telemark > Buskerud > Østfold >

> Hedmark = Oppland = Aust-Agder > Vestfold

PB: Akershus-Oslo > Telemark > Vest-Agder > Buskerud > Vestfold >

> Østfold > Aust-Agder > Oppland > Hedmark

Hg: Akershus-Oslo > Vest-Agder > Telemark > Buskerud > Oppland >

> Østfold > Vestfold > Hedmark > Aust-Agder

Ni: Vest-Agder > Akershus-Oslo > Telemark > Østfold > Buskerud >

> Vestfold > Hedmark > Oppland > Aust-Agder

Zn: Vest-Agder > AKershus-Oslo > Buskerud > Telemark > Østfold >

> Vestfold > Oppland > Hedmark > Aust-Agder

Cu: Akershus-Oslo > Telemark > Buskerud > Vest-Agder > Østfold >

> Oppland > Vestfold > Hedmark > Aust-Agder

Cr: Akershus-Oslo > Telemark > Aust-Agder > Vest-Agder > Buskerud >

> Oppland > Østfold > Vestfold > Hedmark

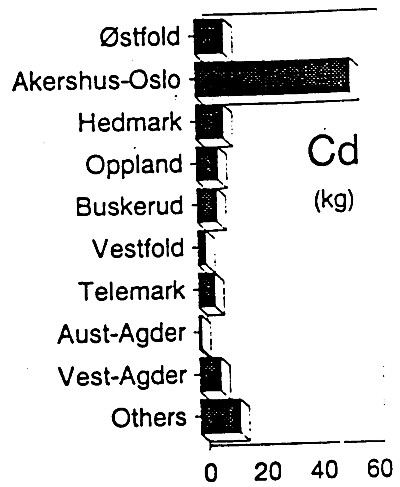
Heavy metal concentrations in sludge in different countries

The concentration of heavy metals in the sludge is an important index for sludge quality. Although, in the most restrictive group in regulations on disposal of sewage sludge, Norway has set higher maximum permissible concentrations of heavy metals in sludge in most cases than Sweden (Vigerust and Wu 1994), the weighted average concentrations of heavy metals in the sludge produced in Norway is generally lower than those in other countries including Sweden (Figure 7). Thus, the sludge produced in Norway has the best quality for use in agricultural recycling.

Fig. 5. Annual quantity of heavy metals generated from sludge in different counties of Norway.

(Aquateam Norway 1994;

(Statistics Norway 1994)



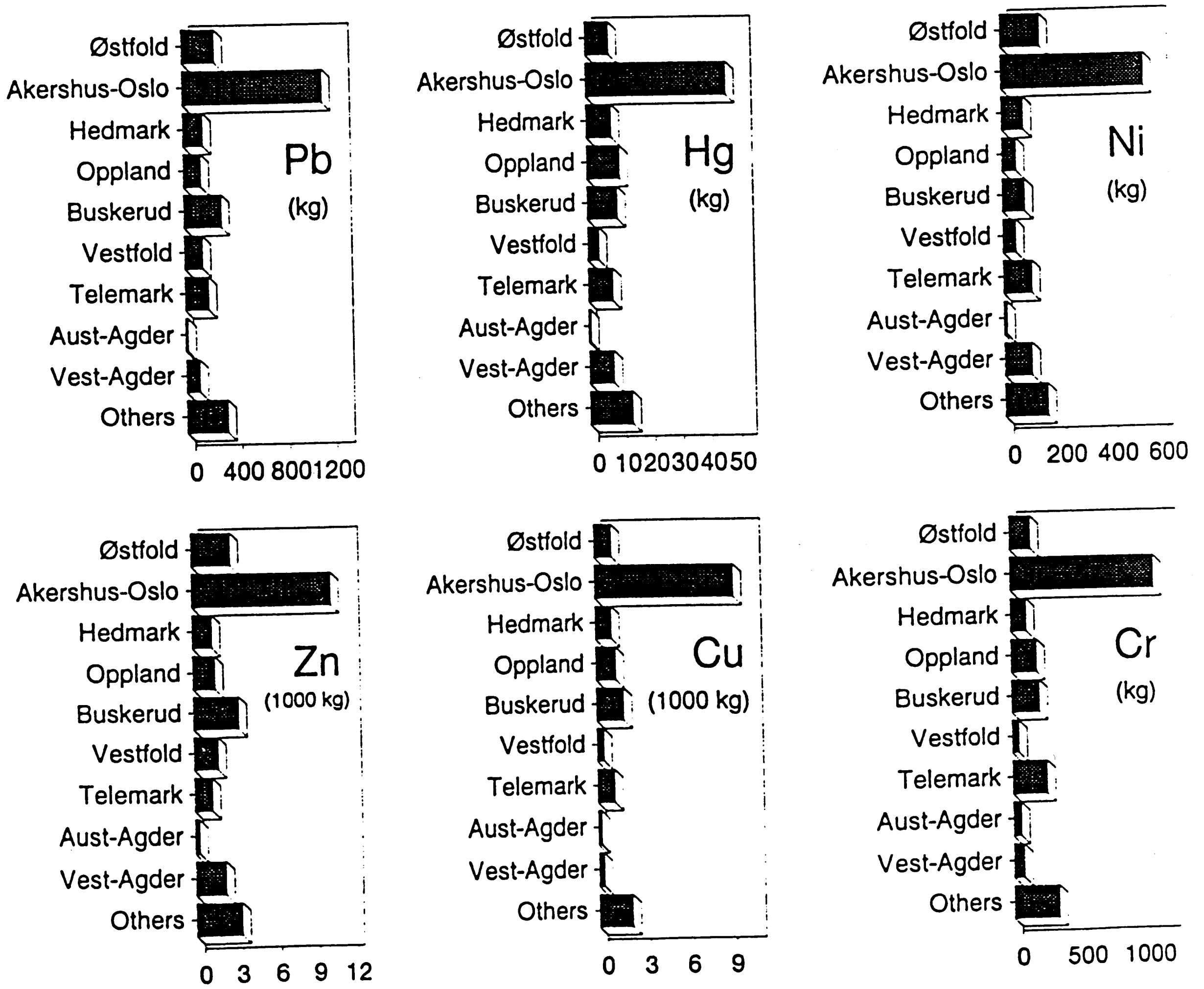
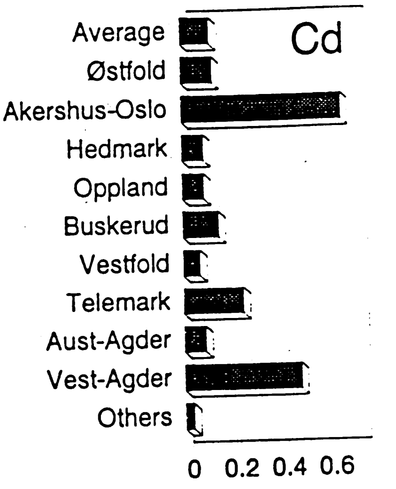


Fig. 6. Annual average loading rates of heavy metals generated from sludge onto cultivated soils excluding fields for growing vegetables.

(g/ha)

(Aquateam Norway 1994;
Statistics Norway 1993; 1994)



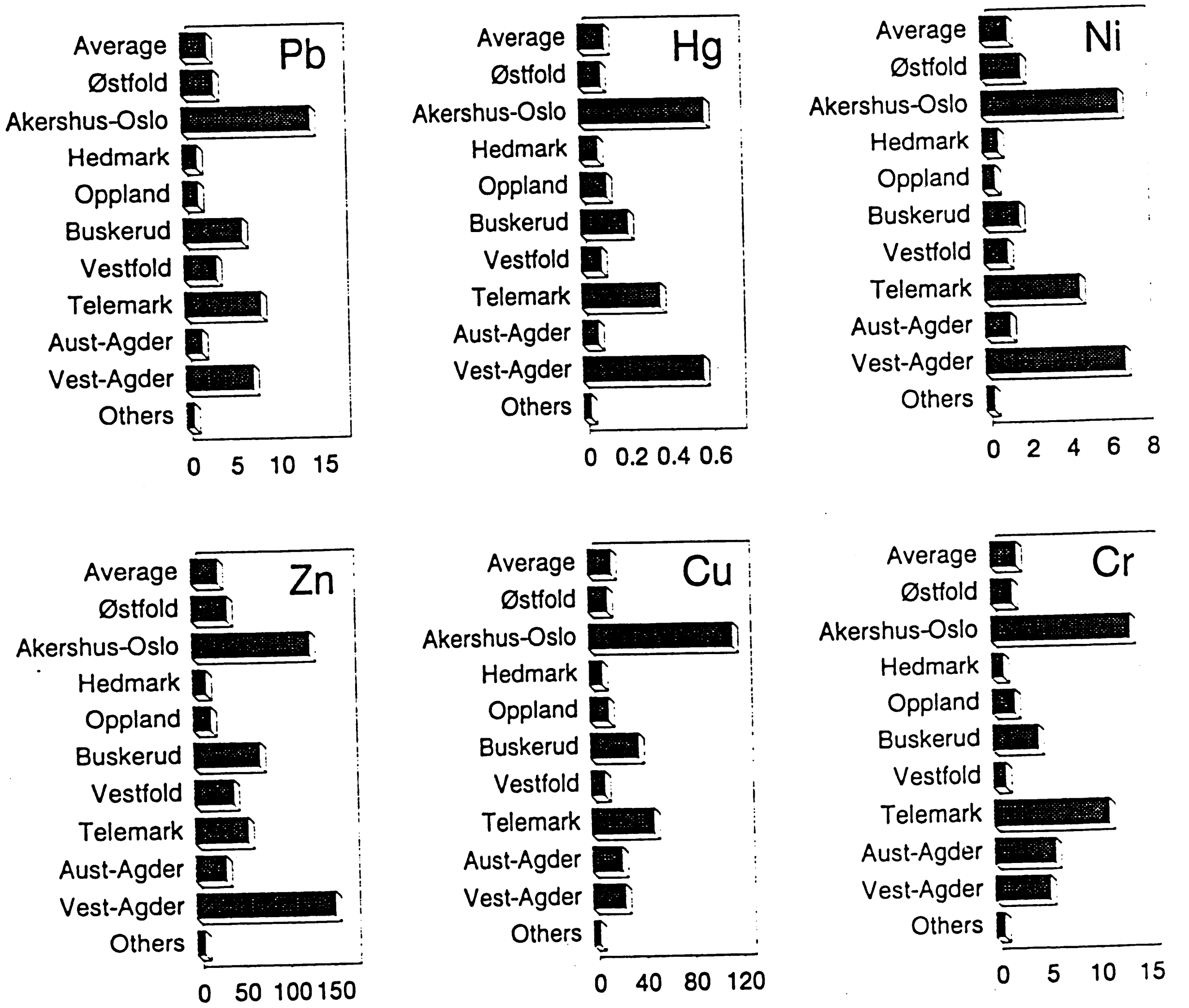
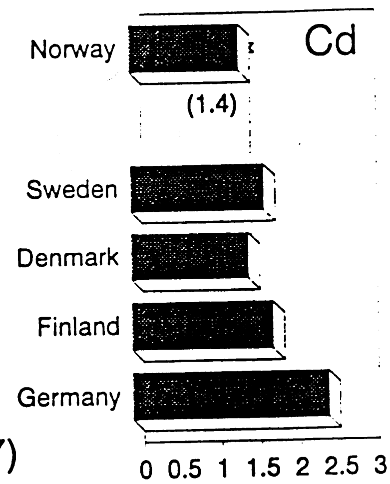
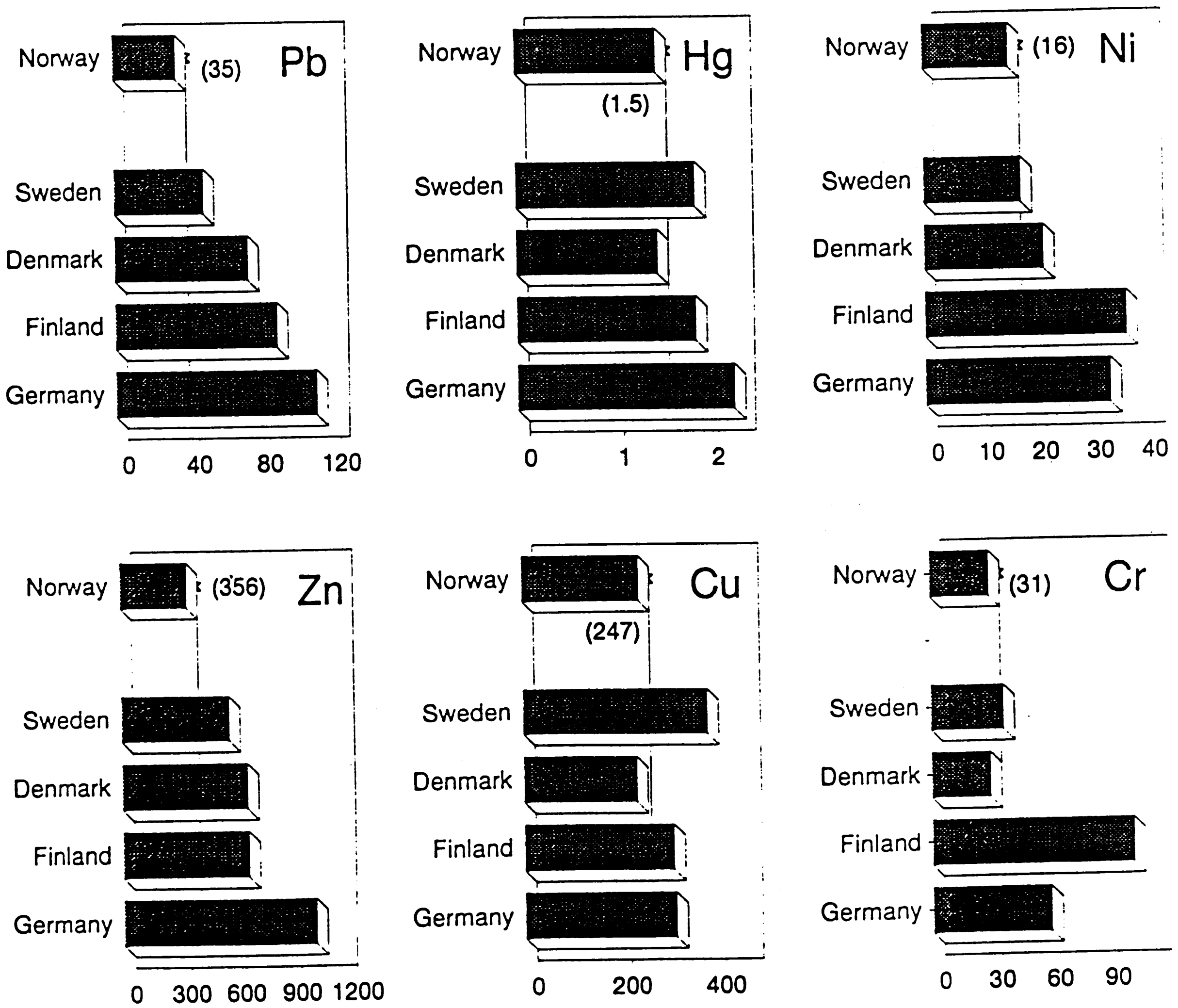


Fig. 7. Comparison of heavy metal concentrations in sludge produced in different countries (mg/kg DS).

(Figures in brackets are the values estimated for Norway using data for 1993; Data for Sweden: 1992; Denmark: 1992; Finland: 1992; Germany: 1991)

(Sources refer to Appendix 7: Data for Fig. 7)





Heavy metals from fertilizers

Phosphorus application

Phosphate fertilizers have been generally recognized as carriers for Cd although they also contain small amount of other heavy metals. Since other types of fertilizers have much lower contents of all the seven concerned heavy metals than phosphorus-containing fertilizers (Bøchman et al. 1990), soil heavy metal input due to fertilization can be calculated on the basis of phosphorus application.

The total amount of phosphorus used in agricultural production in 1994 in Norway is 136,880 tons (Norsk Hydro 1994). Dividing it by the total cultivated agricultural area, 833,090 hectares (Statistics Norway 1993) gives an annual average application intensity as 0.016 tons of phosphorus per hectare (P T/ha/yr) (Table 3). The quantity and intensity based on agricultural areas for different regions in Norway are shown in Figure 8. In comparison, Hedmark has the highest quantity but Vestfold and Østfold have the highest intensity of phosphorus application.

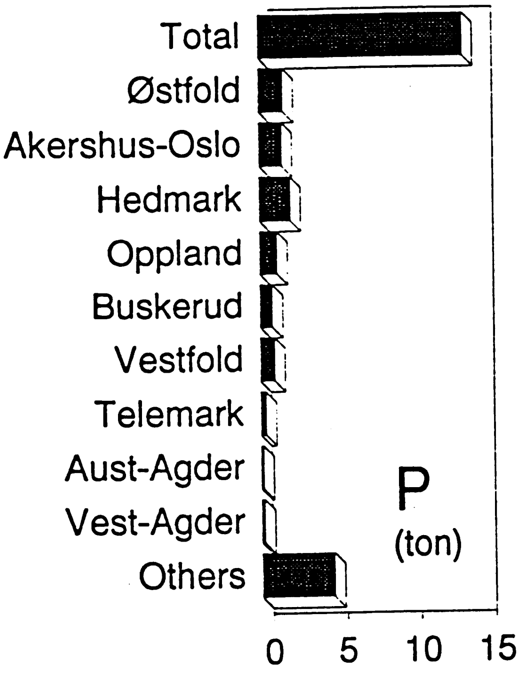
Table 3. Annual phosphate fertilizer application in Norway (Norsk Hydro 1994; Statistics Norway 1993).

Total phosphorus application (Ton)	Total cultivated area (1000 ha)	Average phosphorus application rate (kg/ha/yr)	Range of phosphorus application rate (kg/ha/yr)
13,688	883,090	16.0	9 - 22

Heavy metal concentrations in phosphate fertilizers

The concentrations of heavy metals in phosphate fertilizers vary to a great extent, depending on the origin and the type of parent rocks used for commercial fertilizer production. Table 4 indicates that the concentrations of all seven heavy metals in fertilizers used in Norway are much lower than the average values in the world. The value for Cd concentration, 6.85, in Table 4, is the weighted mean value for Norway, given as the ratio of the total quantity of cadmium generated from phosphate fertilizers to the total quantity of phosphorus applied in the period between July 1993 and June 1994, namely the fertilization year of 1994. The maximum concentration of Cd in phosphate rocks permitted to be used in Norway is 100 mg per kg of phosphorus (mg/kg P) while the highest Cd concentrations found in the fertilizers produced in Norway is 80.3 mg/kg P (Table 5). The majority of fertilizers has a Cd concentrations less than 0.7 mg/kg P (Table 5).

Fig. 8. Phosphate Fertilizer application in different counties of Norway during the period between July 1993 and June 1994 (Norsk Hydro 1994).



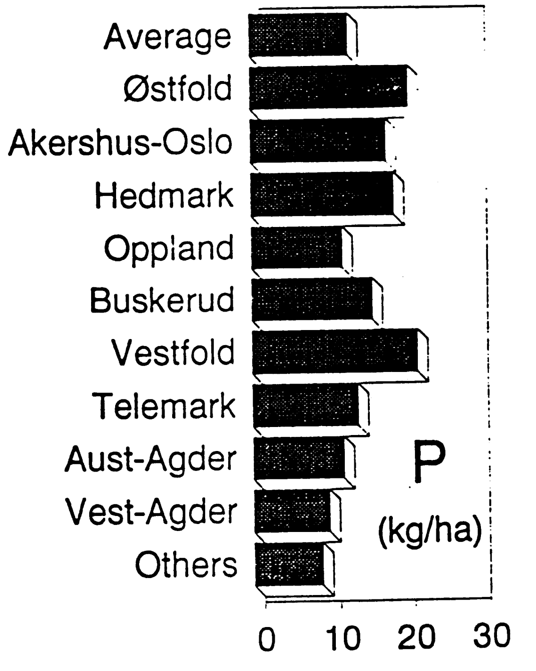
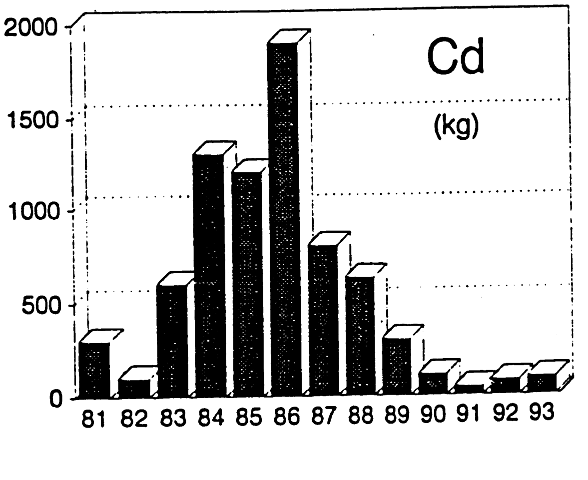


Fig. 9. Soil cadmium input due to phosphorus application in Norway (Norsk Hydro, 1994).



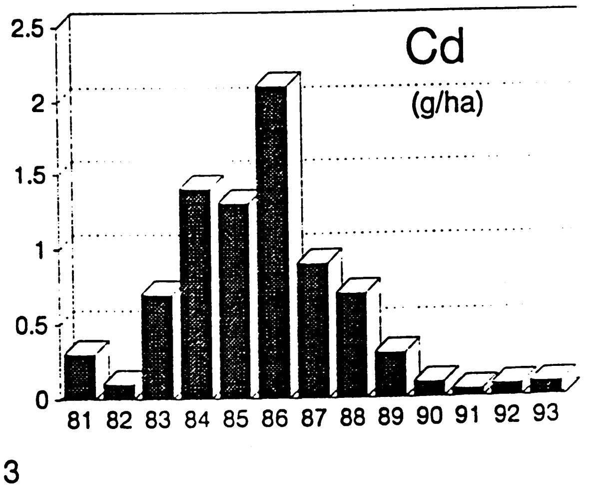


Table 4. Heavy metals in phosphate fertilizers (Bøckman et al. 1990; Norsk Hydro 1994) (mg/kg P).

Metals	Average	Fertilizer in Norway
Cd	170	6.85*
Pb	40	30.00
Hg	0.2	0.1
Ni	230	30.00
Zn	660	100.00
Cu	200	170.00
Cr	1000	60.00

**: The value 6.85 mg/kg P is given as weighted average Cd concentration in P-containing fertilizers used in Norway.*

Table 5. Cadmium concentrations in different types of commercial fertilizers in Norway (Norsk Hydro 1994)

Types	mg/kg P	ton P applied	%
Major NPK fertilizer	0.65	12621.5	92.2
NPK 6-7-21	45.75	42.8	0.3
NPK 25-3-6	80.35	833.9	6.1
KS-Bor	1.75	4.0	<0.1
PK 9-16	8.00	0.6	<0.1
PK 7-18	50.00	74.9	0.5
PK 7-21	52.77	6.5	<0.1
Pk 11-21	53.76	22.3	<0.2
Superphosphate P9	55.57	72.0	0.5
Raw phosphate	40.00	13.1	0.1
Total	6.85	13688.0	100
MPC*	100.00		

*: MPC, the maximum Cd concentration in phosphate rocks permitted to be used for fertilizer production in Norway.

Heavy metal input due to fertilization

Similar to the cases of sludge, the Cd concentration in the commercial fertilizers and thus the total input of Cd into the soil by fertilization have been greatly reduced in the recent years because of using kola phosphate rocks that contain very small amount of heavy metals (Figure 9). According to Norsk Hydro (1993; 1994), the total annual amount of Cd that has been brought into soil as a consequence of fertilization is approximately 94 kg in both 1993 and 1994, which is much lower than the quantity, 1,900 kg, in 1986.

Figures 10 and 11 further show, respectively, the total and average quantity of soil heavy metal input due to use of phosphate fertilizers in different regions of Norway. The calculation of the data used in Figures 10 and 11 for Cd are based on the amount of different types of phosphorus fertilizers applied in different counties of Norway during the period between July 1993 and June 1994 and the concentrations of Cd in different types of phosphate fertilizers given in Table 5. The data for concentrations of other heavy metals in different types of fertilizers applied in 1994 are not available. Thus, the values presented in Table 4 for fertilizers applied in Norway have been used for all counties under the consideration that the commercial fertilizer as a source of other heavy metals is less important compared to that of cadmium and the variation in their concentrations in different fertilizer types in Norway is also small. The average heavy metal input given in g/ha/yr is based on the total cultivated agricultural area including vegetable fields.

As soil heavy metal input by fertilization is determined by the quantity of phosphorus application, the patterns of both quantity and intensity of heavy metal input for all metals including Cd shown in Figures 10 and 11 are essentially the same as, respectively, those of quantity and intensity of phosphorus application shown in Figure 8, namely, Hedmark has the highest quantity input (Figure 10) while Vestfold has the highest intensity input (Figure 11) for all heavy metals, followed by Østfold, Hedmark, Akershus-Oslo, Buskerud, and Telemark. The rest counties have values below the nation's average.

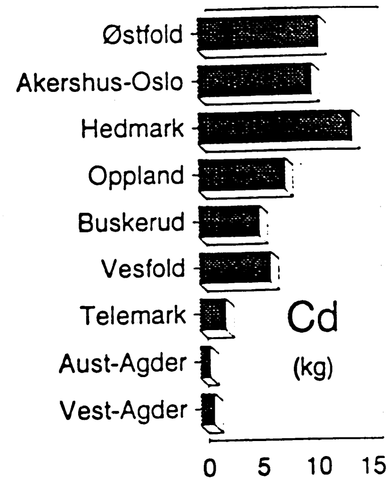
Risk of high cadmium input by fertilization

The quantity of phosphorus application found for 1994 in the present report is 16 kg P per hectare as an average for Norway. According to Gjplan (1990), however, the amount of phosphorus required by crops varies from 20 to 60 kg P per hectare, depending on the soil native P availability, the types of the crops and the intensity of crop production. The reason for the reported average value lower than the required ones is the use of animal manures in certain areas of Norway that reduces the total amount of phosphate fertilizer application in the whole country. As the use of animal wastes is not evenly distributed but limited in regions with high animal production (Tveitnes 1985), the actual amount of phosphate fertilizer application can be much higher than the given mean values in areas with less intensive animal production. Thus higher amount of heavy metal input can be expected in such areas.

It is also noticed in Table 5 that the concentration of Cd in different types of fertilizers used in Norway ranges from 0.65 to 80.3 mg/kg P. Thus the quantity of soil cadmium input in terms of gram per hectare per year is largely subject to the types of phosphorus-containing fertilizers used. Figure 12 shows that the addition of Cd varies from 0.016 to 2.0 g/h/yr for different types of fertilizers given that 25 kg of phosphorus be supplied to the soil using commercial fertilizers. Recommendation based on soil native cadmium levels should be given for choosing the right type of phosphate fertilizers particularly in areas where less animal wastes are used in agriculture.

Fig. 10. Heavy metals generated from phosphorus fertilizers applied in the period between July 1993 and June 1994 in different counties of Norway.

(Norsk Hydro 1994)



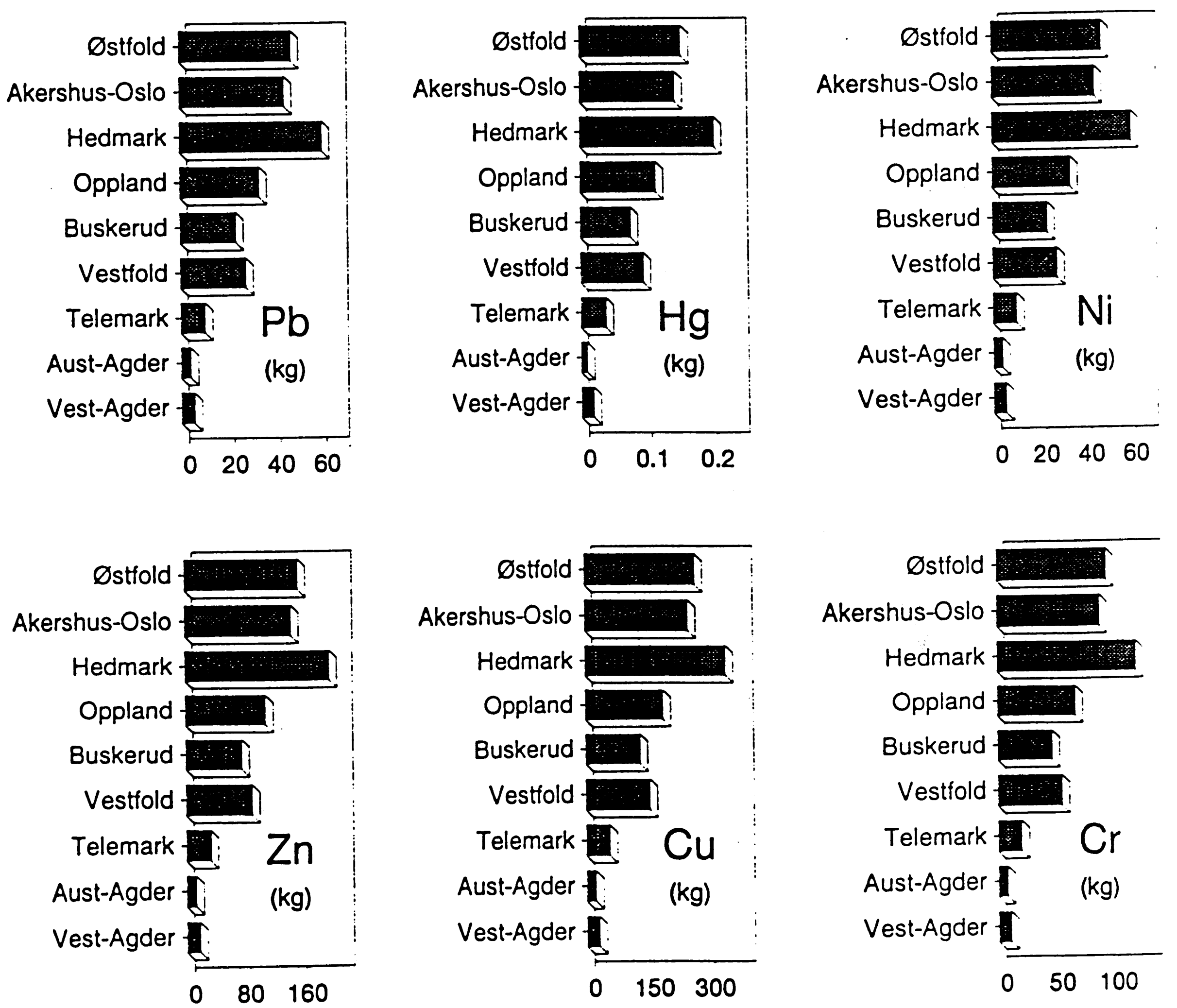
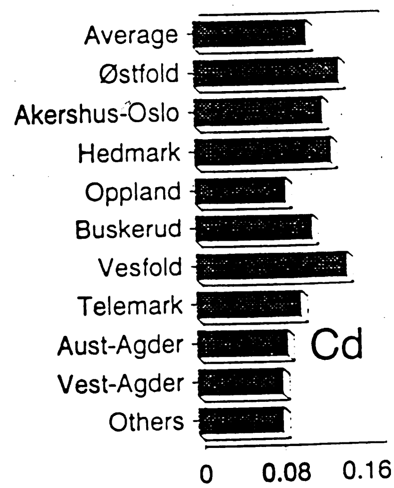


Fig. 11. Average loading rates of heavy metals due to application of phosphorus fertilizers onto Norwegian cultivated soils in the period between July 1993 and June 1994.

(Norsk Hydro 1994;
Statistics Norway 1993)

(g/ha/yr)



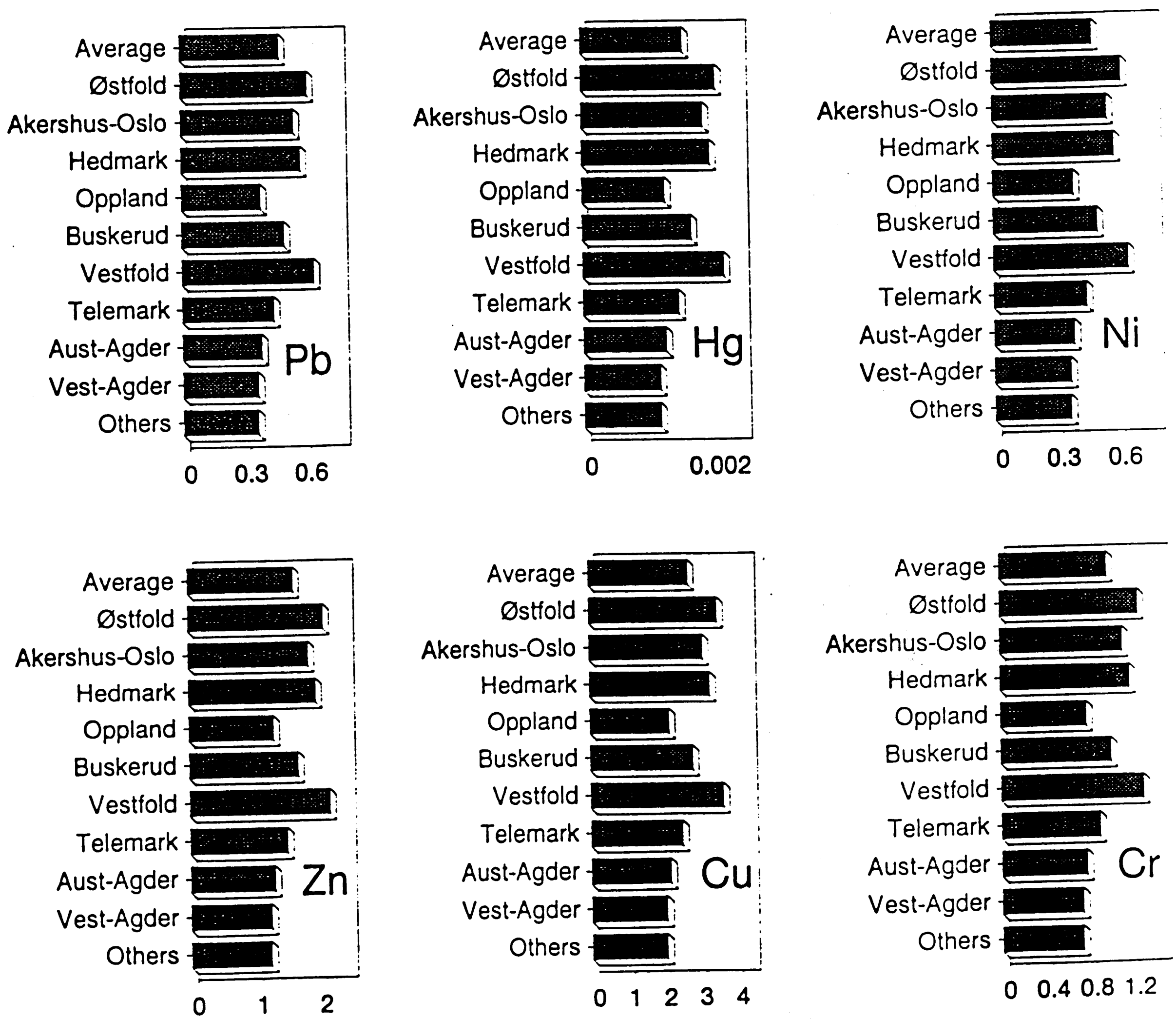
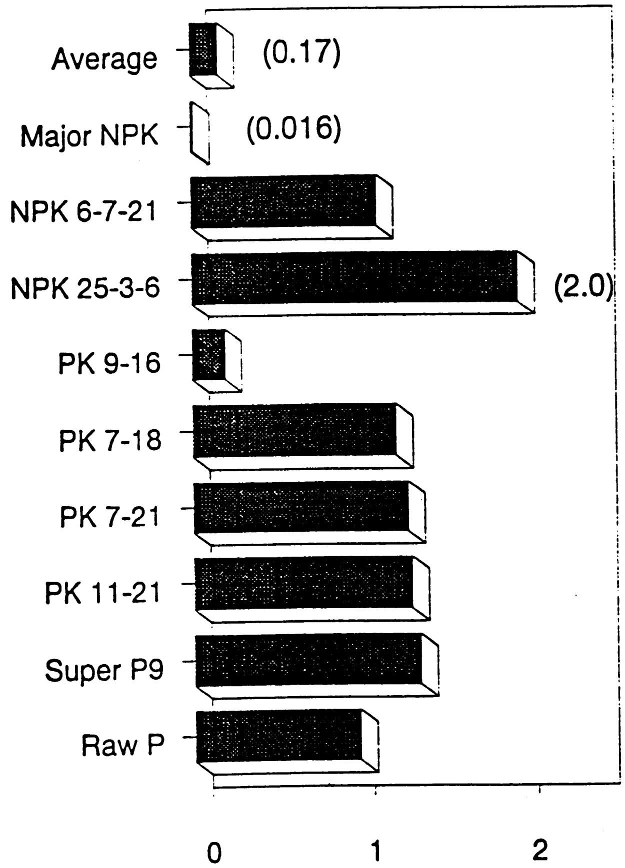


Fig. 12. Soil Cd addition due to use of different types of phosphate fertilizers given that 25 kgs of P per hectare are annually applied (Norsk Hydro 1994).

(Cd g/ha/yr)



Heavy metals from atmospheric deposition

Heavy metal concentration in precipitation

Significant decrease in cadmium and lead concentrations in precipitation has been observed in different stations of Norway during last decade (Figure 13). The same tendency has also been reported in other Nordic countries as well as in Europe (Hovemand 1992; Nord 1992:12 1992). Such significant changes in atmospheric heavy metals status are of extreme importance as atmospheric deposition as a consequence of industrialization has long been the main source responsible for soil heavy metal accumulations while the control of heavy metal pollution from long-distance air transport has been remaining the most difficult task.

Annual input of heavy metals from atmospheric deposition

The soil input of heavy metals from atmospheric deposition in different counties of Norway is shown in Figure 14 using the data reported for 1992 by SFT rapport: 533/93 (1993). Since the values used are the measures made at the following four observation stations:

Nordmoen: Østfold, Akershus-Oslo and Vestfold;
Osen: Hedmark, Oppland and Buskerud;
Solhomfjell: Telemark; and
Birkenes: Aust-Agder and Vest-Agder,

In comparison, Aust-Agder and Vest-Agder areas have consistently higher amount of air-borne Cd, Pb and Zn than the other counties listed in Figure 14. Due to lack of information for Hg, Ni, Cu and Cr for several regions, the data from the Solhomfjell Station are used to represent the average value for the whole country. Table 6 shows that the suggested average values based on reports from SFT-rapport (1993) are more close to those given by Andersson (1992) but much lower than those reported by Kongshaug (1992).

Table 6. Average input of heavy metals from atmospheric deposition (g/ha/yr).

Sources	Cd	Pb	Hg	Ni	Zn	Cu	Cr
Suggested average (SFT-rapport 1993)	0.35	21.9	0.2	2.86	46.0	6.26	2.81
Anderssion 1992							
A*	1.1	35	0.2	3.0	110	12.0	1.2
B	0.78	22	0.15	3.0	85	7.5	1.2
C	0.9	30	0.15	3.0	100	11.0	1.2
D	0.4	15	0.07	3.0	65	7.0	1.2
Kongshaug 1992	3.0	200	2.0	30.0	400	20.0	4.0

*: Data given by Andersson (1992) are values for different locations.

Fig. 13. Concentrations of heavy metals in precipitation determined for different years at different observation stations of Norway (ug/L).

(SFT Rapport 533/93 1993)

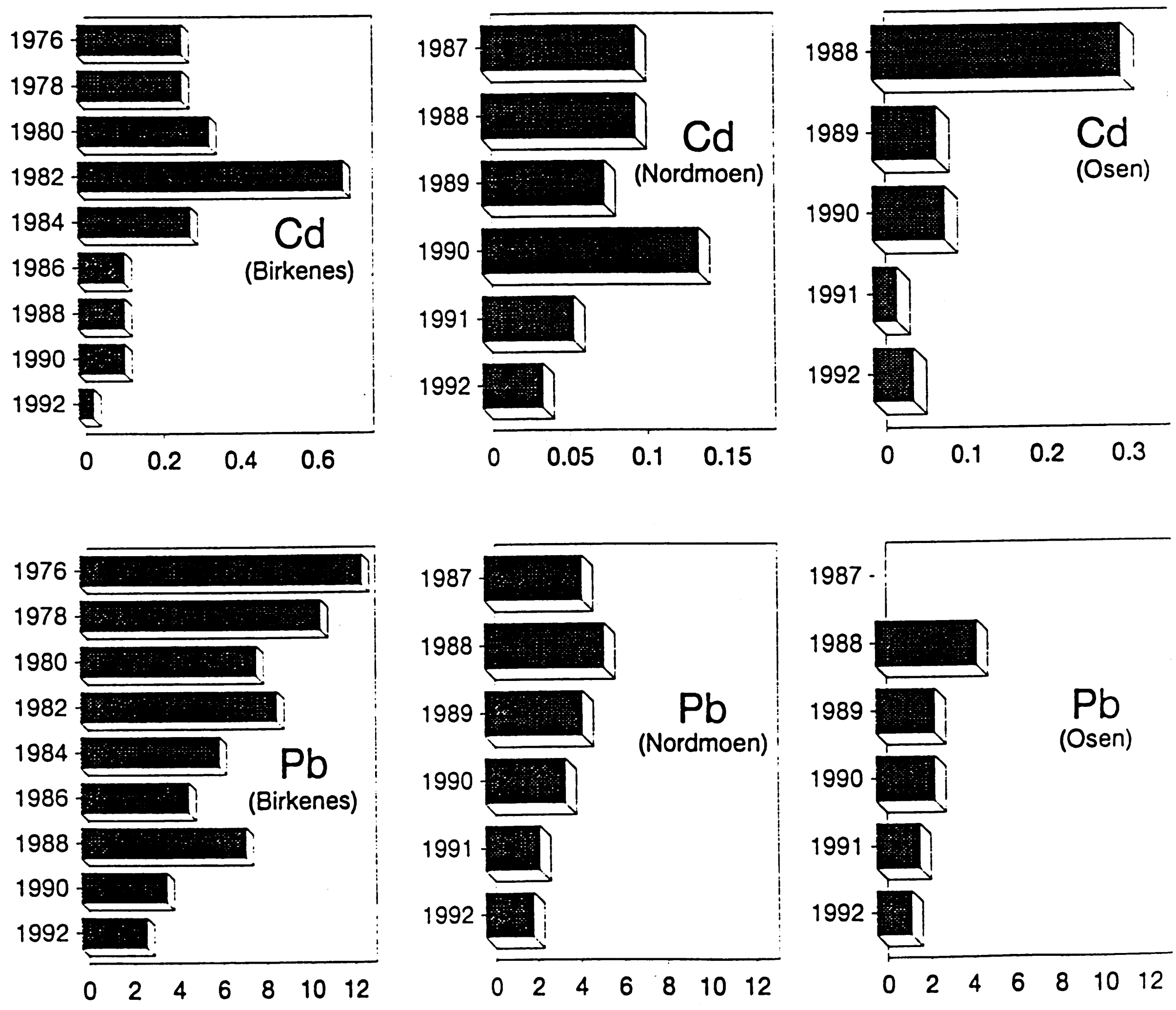
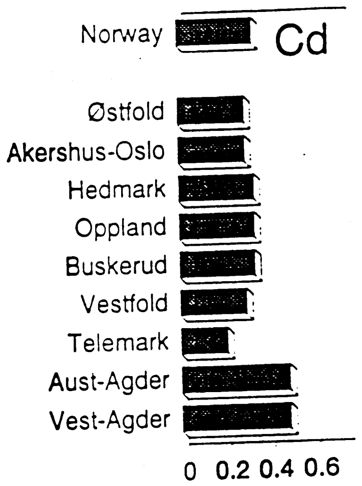
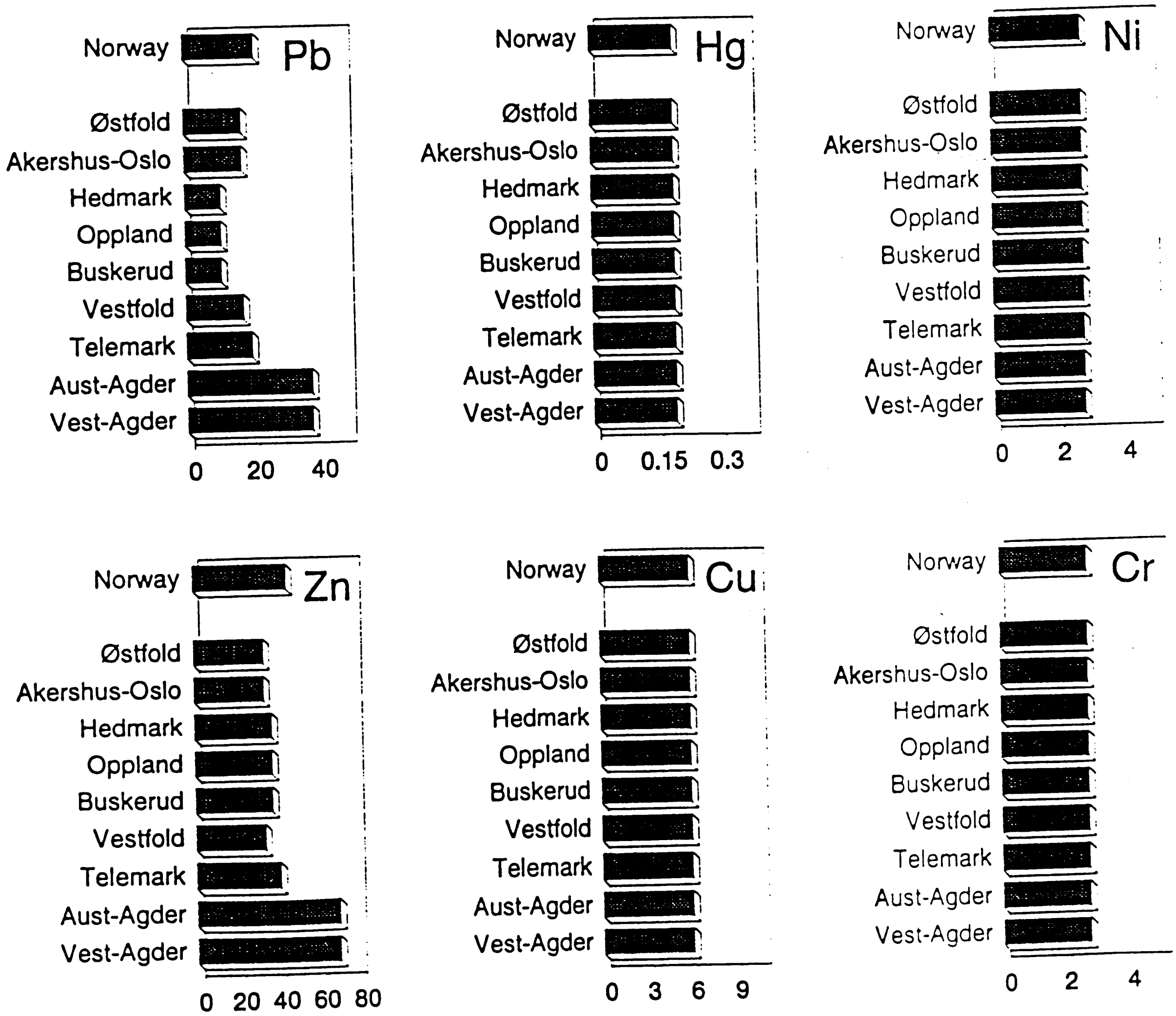


Fig. 14. Soil input of heavy metals from atmospheric deposition in different counties of Norway.

(SFT Rapport 533/93 1993; Statistics Norway 1994)

(g/ha/yr)





Removal of heavy metals from soil

Heavy metals are removed from soil by plant uptake and leaching. Estimation of the annual removal quantity presents great difficult because the magnitude is subject to number of factors such as crop types and rotations, soil types, geographic conditions, and the availability of the soil heavy metals. It can be argued that a reasonably higher value of soil heavy metal removal due to plant uptake can be chosen because if heavy metal accumulation occurs and consequently increases the soil heavy metal mobility or availability, both plant uptake and leaching will be increased until balance is reached between soil metal input and output. Thus use of a higher value of soil heavy metal output in the normal range, namely,a range that has been proven to be safe to organisms should be more adequate than use of a lower one to prevent under-estimation of soil heavy metal removal.

Heavy metal uptake

For estimation of plant uptake of heavy metals in different counties of Norway, the total crop production reported by Statistics Norway (1993) has been used as basis for the calculations under the consideration that the reported values represent that proportion of yield removed from the farmlands (Table 7). Proposed concentrations of heavy metals in different types of crops are presented in Table 8, which are considered as reasonable average concentrations based on values reported for crops grown in Norway by different authors (Låg and Steinnes 1977; Aasen 1986; Wu & Aasen 1994; Wu and Selmer-Olsen 1992).

Table 7. Crop production in Norway reported by Statistics Norway (1993) (1000 tons).

	Wheat grain	Barley grain	Oats grain	Oil-seed	Potato	Root (feed)	Fodder	Hay
Total	192.5	488.0	325.4	7.7	510.8	91.8	913.2	3081.6
Østfold	55.8	56.2	74.2	2.1	36.1	8.5	27.0	48.3
Akershu-Oslo	30.4	61.5	83.9	1.2	18.8	2.4	23.2	56.6
Hedmark	37.4	95.9	89.1	0.9	144.8	8.4	59.7	164.8
Oppland	12.3	63.3	10.3	0.7	69.8	9.2	92.1	262.7
Buskerud	18.3	25.2	21.5	0.1	15.4	6.4	18.1	66.9
Vestfold	32.1	25.5	23.0	1.4	63.0	7.4	11.4	18.2
Telemark	4.3	12.7	7.4	0.1	11.7	1.0	12.8	35.9
Aust-Agder	0.3	2.5	0.6	0.1	6.8	2.0	6.0	37.5
Vest-Agder	0.1	0.7	1.1	0.1	3.1	1.4	14.6	77.5
Others	1.7	144.6	14.4	1.0	141.8	45.1	648.6	2313.2

Table 8. Proposed average concentrations of heavy metals in different types of crops (mg/kg on air-dry weight basis, except for potato).

		Cd	Pb	Hg	Ni	Zn	Cu	Cr
Wheat	Grain	0.06	0.06	0.002	0.40	27.0	5	0.02
	Straw	0.11	0.45	0.02	0.21	9.4	1.3	0.16
Barley	Grain	0.02	0.06	0.003	0.20	32.0	6.0	0.03
	Straw	0.12	1.10	0.02	0.40	14.0	3.3	1.30
Oats	Grain	0.03	0.06	0.003	1.00	34.0	5.0	0.03
	Straw	0.13	1.3	0.016	0.63	19.0	4.3	0.15
Green fodder		0.05	1.0	0.005	1.00	25.0	6.0	0.11
Oil seed		0.07	0.2	0.005	0.46	38.0	3.0	0.02
Potato		0.02	0.02	0.002	0.10	4.1	1.0	0.005
Roots as feeds		0.04	0.14	0.001	0.10	7.2	1.4	0.13
Hay		0.12	1.10	0.02	0.40	14.0	3.3	0.13

Table 9. Proposed maximum tolerant concentrations of heavy metals in crops (mg/kg on dry weight basis, except for potato) (EK-Livs 1993).

	Cd	Pb
Potato	0.05	0.1
Vegetables	0.1	0.3
Cereals	0.1	0.1

The most suitable values for estimating heavy metal uptake should be the maximum permissible concentrations of heavy metals in different types of crops as they are in principal the upper limits of adequate concentrations, in accordance with the maximum limits in sludge, phosphate rocks and soils. Such limits values, however, have not been established in Norway, and neither fully legislated in other countries, except for some of the proposed maximum tolerant concentrations for certain crops listed in Table 9. Studies on maximum permissible limits for heavy metals concentrations in different types of crops should be of essentially importance as it is finally these limits that are concerned with respect to heavy metal contaminations.

The average of values of heavy metal uptake by crops for Norway so estimated are given in Table 10 while those for different counties are shown in Figures 15 and 16.

The two counties, Hedmark and Oppland, have much higher annual quantity of heavy metal uptake for all seven elements than the other regions (Figure 15). The reason for this is that these two counties, particular Oppland, have the highest hay production (Table 7), which, accounted for further by its highest heavy metal concentrations compared to those concentrations in grains, seeds and other crops (Table 8), contribute the major proportion of heavy metal uptake. This picture is more clear when comparing the average heavy metal uptake per unit cultivated area in different counties (Figure 16). The highest heavy metal removal rates in grams per hectare of cultivated area per year (g/ha/yr) due to plant uptake is in the less intensive agricultural production areas, which are denoted as Others in Figure 16, followed by Vest-Agder, Oppland and Hedmark. The straws from wheat, barley and oats are mostly returned to the fields in the main agricultural areas and less used as feeds due to small scale of animal production. The annual removal rates of heavy metals by plant uptake in Østfold, Akershus-Oslo, Buskerud and Vestfold could be much higher than those values in Figures 15 and 16 if straw productions of cereal crops in these areas were also included in the yield reports.

Table 10. Removal of heavy metals due to crop production in Norway based on crop yield reported for 1992 by Statistics Norway (1993).

	Cd	Pb	Hg	Ni	Zn	Cu	Cr
Total (kg)	461.0	4388	70.2	2710	100897	21837	544.0
Average (g/ha/yr)	0.52	4.97	0.08	3.07	114.3	24.73	0.62

Heavy metal leaching

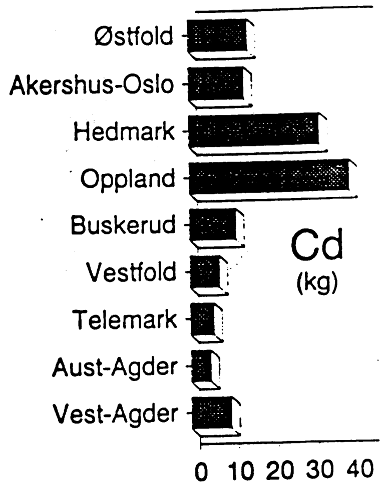
There is very few information on leaching of heavy metals available in Norway. Table 11 gives the suggested values in comparison with those used by Andersson (1992). As the final targets of the leached heavy metals are the water resources, high levels of metal leaching are undesirable though it is a process of heavy metal removal from the soil. The suggested values indicated in Table 11 are used for all counties of Norway. Although actual leaching rates vary with localities, the argument holds that, similar to that of plant uptake, leaching is a process subject to dynamic balance and the suggested levels will be reached with increase in heavy metal mobility, provided that these suggested levels are not harmful to the environment. It should also be desirable to establish experimental stations in different regions to investigate or monitor annual heavy metal leaching rates, thus providing more accurate data for estimation of soil heavy metal removal.

Table 11. Annual leaching rates of soil heavy metals (g/ha/yr).

	Cd	Pb	Hg	Ni	Zn	Cu	Cr
Anderssion 1992	0.06	0.50	0.01	3.9	7.5	4.3	0.70
Suggested data	0.10	0.60	0.01	4.0	8.0	4.0	0.80

Fig. 15. Total quantity of heavy metals taken up by crops in different counties of Norway (Data are based on the production of different types of crops in 1992 in different counties and the heavy metal concentrations given in Table 8).

(Andersson 1992; Låg and Steinnes 1977; Statistics Norway 1993; Wu and Aasen 1994; Wu and Selmer-Olsen 1992;)



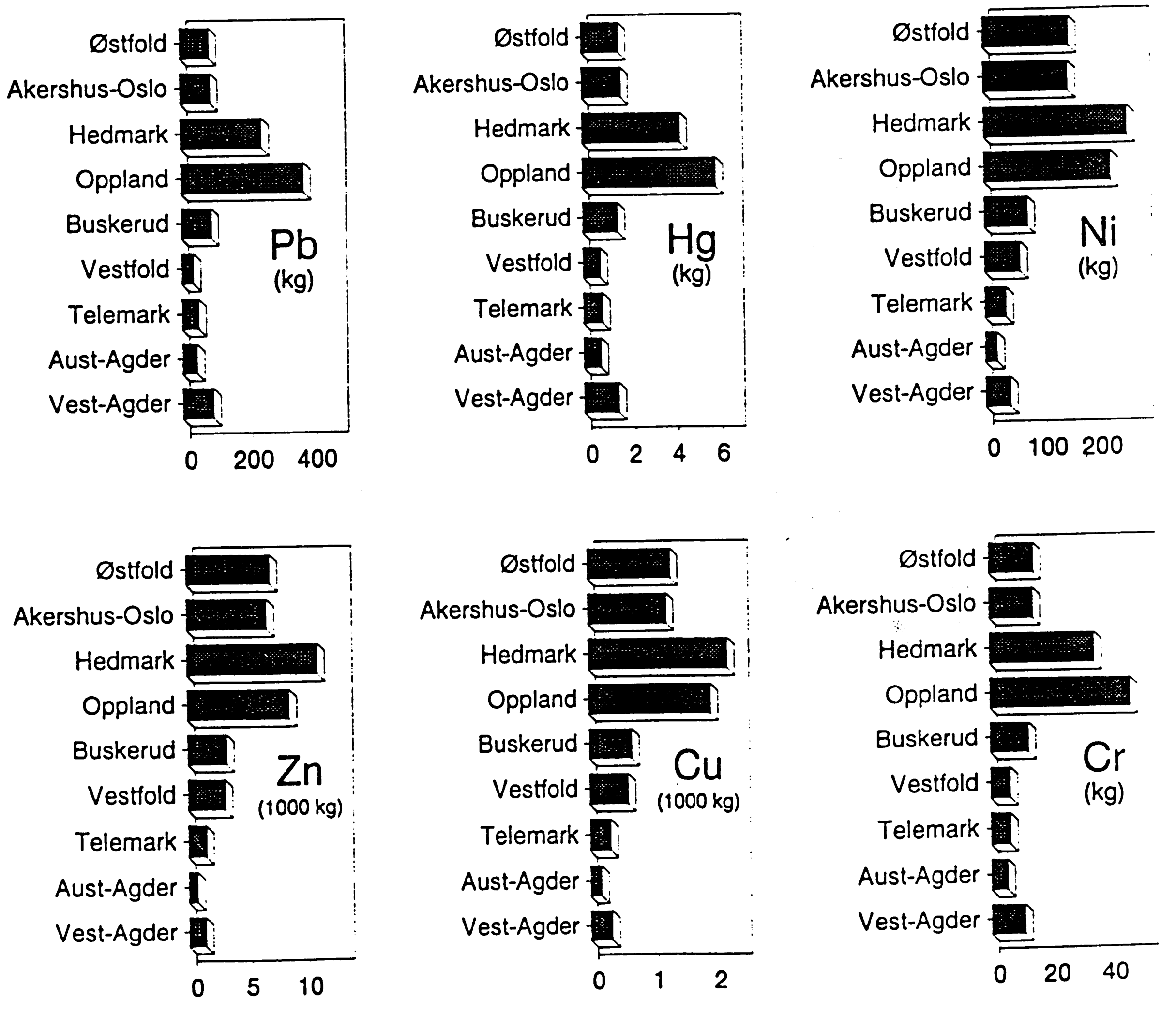
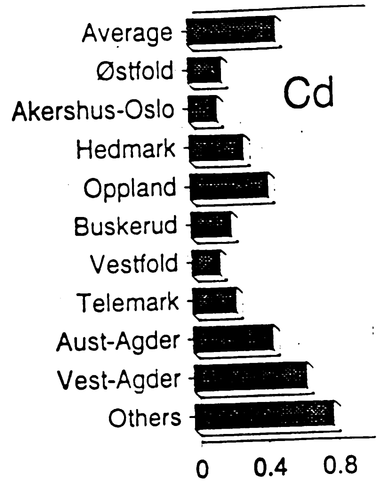
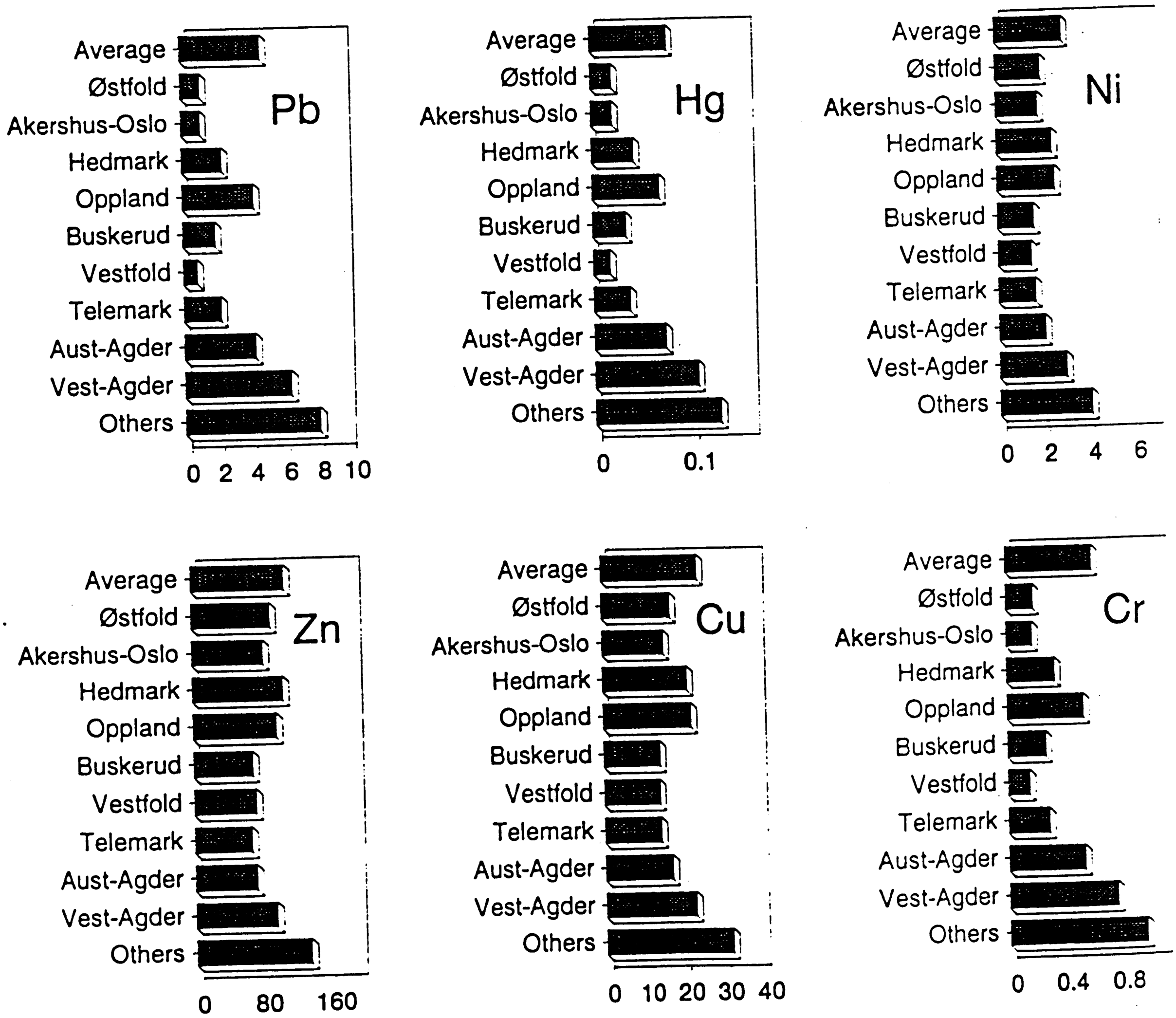


Fig. 16. Uptake of heavy metals by crops in different counties of Norway (Data are based on the production of different types of crops in 1992 in different counties and the heavy metal concentrations given in Table 8).

(Andersson 1992; Låg and Steinnes 1977; Statistics Norway 1993; Wu and Aasen 1994; Wu and Selmer-Olsen 1992;)

(g/ha/yr)





Soil heavy metal fluxes

Average fluxes

Figure 17 illustrates the fluxes of soil heavy metals based on the nation's average heavy metal input due to sludge application with an annual sludge loading rate as 0.10 T DS/ha (Table 1), phosphate fertilization with an annual phosphorus application rate as 16 kg/ha (Table 3) and atmospheric deposition (Table 6), and output due to plant uptake (Table 10) and leaching (Table 11).

For soil heavy metal input rates, atmospheric deposition is shown to be the most important source for Cd, Pb, Hg, Ni, Zn, and Cr while sludge, to be the most important source for Cu. In all cases, fertilization contributes the least proportion to soil heavy metal input. In comparison for the output rates, crop uptake removes more Cd, Pb, Hg and particularly the two micro-nutrients, Zn and Cu, but slightly less Ni and Cr than leaching (Figure 17).

It is interesting to see that, based on the average values, the soil input rates of Cd, Ni and Zn are lower than the output rates of these three metals, while the soil fluxes of Cu are nearly balanced. According to Aasen (1986) and Wu and Selmer-Olsen (1992), the adequate concentration of Cu in wheat and barley grains can range from 5 to 15 mg/kg. Thus, higher Cu removal rates by plant uptake can be expected than the presently used values.

The input rates of Pb, Hg and Cr are much higher than their output rates (Figure 17). Atmospheric deposition is apparently the major source for all the three elements and next is sludge. Fertilization also brings small but significant quantity of Cr to the soil compared to its removal rate. The metal input due to atmospheric deposition can even be higher if further including the proportion of dry deposition, which, in general, accounts for approximately 15% of the total air-born heavy metals in the soil. As a matter of fact, soil input rates of these three metals, Pb, Hg and Cr, from atmospheric deposition along are higher than their output rates in most of the counties listed and thus, balance of soil Pb, Hg and Cr fluxes can hardly be reached in Norway.

Based on the nation's average basis, the sources of soil heavy metal input as well as the order of importance can be grouped as follows:

Cd: atmospheric deposition > sludge application > fertilization

Pb: atmospheric deposition

Hg: atmospheric deposition > sludge application

Ni: atmospheric deposition > sludge application > fertilization

Zn: atmospheric deposition > sludge application

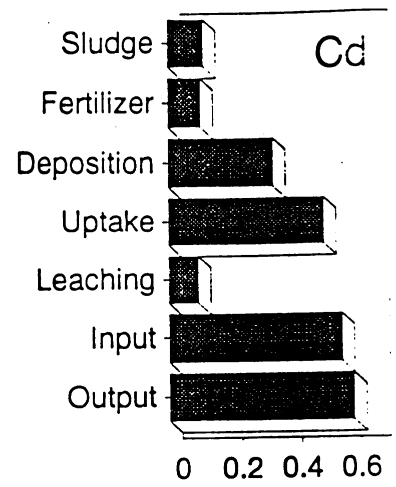
Cu: sludge application > atmospheric deposition > fertilization

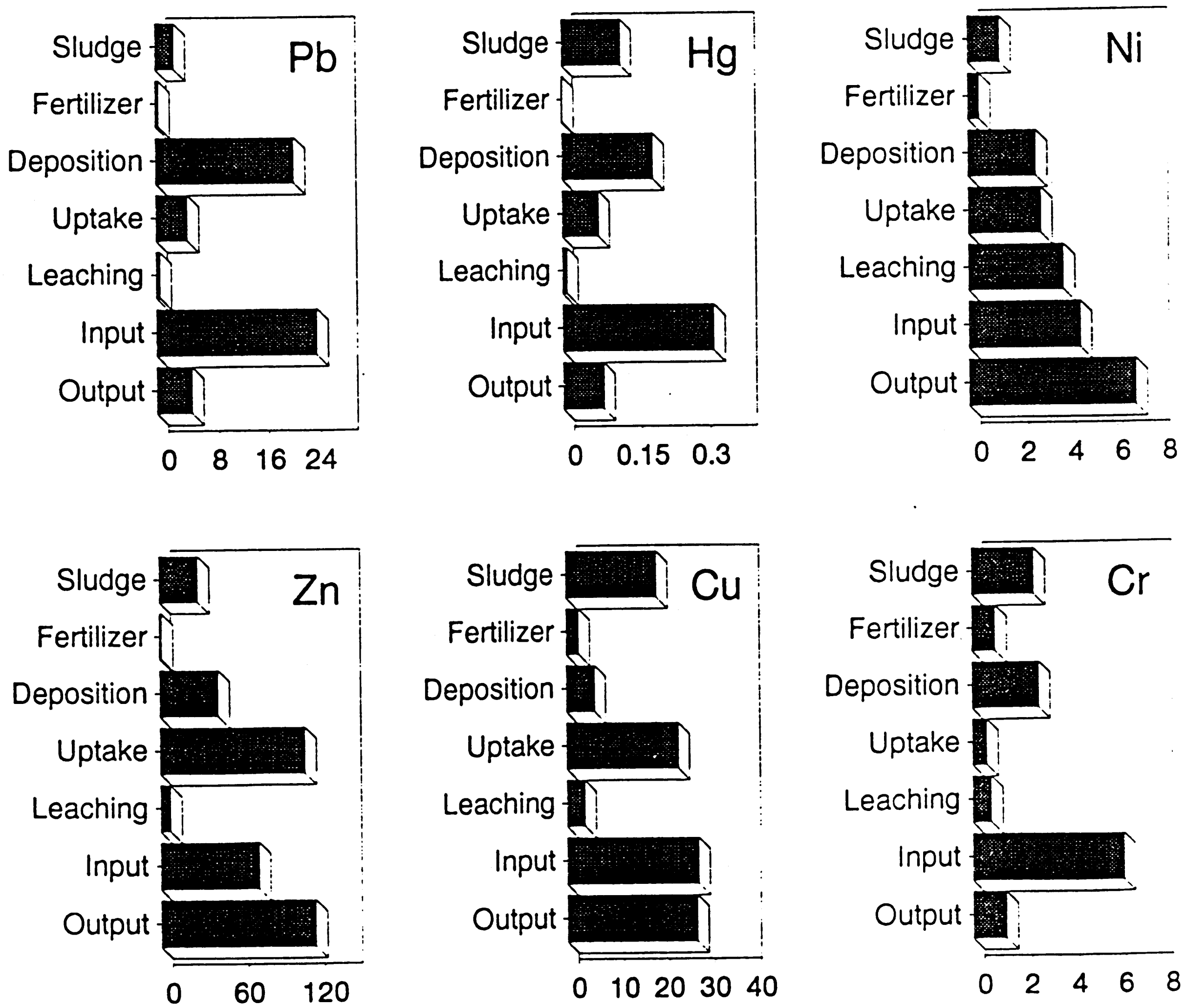
Cr: atmospheric deposition > sludge application > fertilization.

Fig. 17. Soil heavy metal input due to sludge application, fertilization, and atmospheric deposition, and output due to plant uptake and leaching.

Average (g/ha/yr)

(Andersson 1992; Norsk Hydro 1994; SFT-rapport 533:93 1993; Statistics Norway 1993; 1994)





In general, it can be concluded that in Norway today, atmospheric deposition is still the most important source responsible for soil heavy metal input. Sludge application may give risk to soil heavy metal contamination, depending largely on its loading rate. Fertilization does not play important role in this respect except for use of those types of fertilizers with high cadmium concentrations.

Maximum number of years for sludge application

The pattern shown in Figure 17 describes a general trend of heavy metal fluxes in Norwegian soils based on the given average sludge production density, 0.10 T DS/ha. The real situation can be completely different if two tons of sludge are annually amended onto one hectare of cultivated lands, as by so the input rate due to use of sludge along will be then increased by 20-fold such that fluxes of all heavy metals can be hardly balanced. On the other hands, however, higher soil heavy metal input than output does not necessarily mean that heavy metals in Norwegian soils would be soon accumulated to harmful levels. According to the report from Amundsen and Vigerust (1994), the heavy metal levels in most of the Norwegian soil are much lower than the legislated maximum permissible limits. Upon the sludge loading rate, 2 T DS/ha, the questions of most concern will turn to be

1. How many years sludge can be applied in Norway without exceeding the legislated maximum permissible limits?
2. Which metal(s) will be the one(s) first reaching its (their) maximum permissible limit(s) and thus limiting the use of sludge in agriculture?
3. To which extent and under which conditions heavy metal uptake and leaching will be increased with increasing soil heavy metal concentration that finally causes problems to the living environment?

The last question is the most difficult one as it concerns the availability of soil heavy metals in relation to their soil quantity, which is subject to number of factors. Figure 18 gives the maximum number of years for sludge application with an annual loading rate as 2 T DS/ha, and further shows the limiting factor(s), referring to the first two questions.

Table 12. Background average concentrations of heavy metals in Norwegian soils (BACso) and those in the sludge produced in 1993 (BACsl) in comparison with the maximum permissible concentrations of heavy metals in the soil (MPCso) and the maximum permissible increase in concentrations of heavy metals in the soil (MPIso, given as the difference between MPCso and BACso) according to Norwegian legislation (Amundsen and Vigerust 1994; Vigerust and Wu 1994).

	Cd	Pb	Hg	Ni	Zn	Cu	Cr
MPCso (mg/kg DS)	1.0	50	1	30	150	50	100
BACso (mg/kg DS)	0.2	20	0.04	23	55	20	30
MPIso (mg/kg DS)	0.8	30	0.96	7	95	30	70
BACsl (mg/kg DS)	1.4	35	1.5	16	356	247	31

On calculation of the maximum number of years for sludge application, the maximum permissible increase in soil heavy metal concentration (MPIso), given as the difference between the maximum permissible concentration and the background average concentration in the soil (Table 12), has been taken as the upper limits for heavy metal addition and the soil weight for one hectare has been assumed to be 3000 tons in dry matter, namely, a hectare of a soil with a depth of 20 cm and a bulk density of 1.5. Thus, the maximum permissible increase in soil heavy metal quantity (MPQ) in grams per hectare (g/ha) will be

$$\text{MPQ} = 3000(\text{MPIso}) \qquad \text{(g/ha)} \qquad (1)$$

Considering that heavy metals are also removed from the soil by crop production and soil leaching, which decreases the soil metal quantity, the real annual increase in soil heavy metal quantity in grams per hectare per year (g/ha/yr) due to sludge application will be the annual input from sludge minus the annual removal by uptake and leaching, i.e.,

$$\text{BAC} = \text{input from sludge} - \text{output due to uptake and leaching} \qquad \text{(g/ha/yr)} \qquad (2)$$

where BAC represents the soil heavy metal increase caused by an annual addition of 2 tons of sludge with heavy metal concentrations (BACsl) given in Table 12. Similarly, the annual increase in soil heavy metal quantity due to sludge application, phosphorus fertilization and atmospheric deposition can be defined as

$$\text{BAC plus other sources} = \text{input from sludge, fertilization and deposition} - \text{output due to uptake and leaching} \qquad \text{(g/ha/yr)} \qquad (3)$$

Then, the maximum number of years for sludge application,

$$\text{No. of years} = (\text{MPQ})/(\text{BAC}) \qquad (4)$$

and that for sludge application plus fertilization and atmospheric deposition,

$$\text{No. of years} = (\text{MPQ})/(\text{BAC plus other sources}) \qquad (5)$$

The maximum number of years for sludge application has been further calculated to county levels in the same way using background average concentrations of heavy metals in soil and sludge and data for phosphorus fertilization, atmospheric deposition, crop production and leaching for related counties.

In contrast to those in Figure 17, the patterns in Figure 18 show that, when 2 tons of sludge are applied, the element that gives the lowest number of years for sludge application is Cu, followed by Zn as well as the other metals in the sequence for BAC,

$$\text{Cu} < \text{Zn} < \text{Ni} < \text{Hg} < \text{Cd} < \text{Pb} < \text{Cr}$$

and for BAC plus other sources,

$$\text{Cu} < \text{Zn} < \text{Ni} < \text{Cd} < \text{Hg} < \text{Pb} < \text{Cr}$$

For both cases, sludge application along (BAC) or with further inclusion of fertilization and atmospheric deposition (BAC plus other sources), the first two limiting factors are the two micro-nutrients, Cu and Zn, while the last two metals are Pb and Cr.

The concentrations of Cu and particularly Zn are considerably higher than those of the other metals in the sludge produced in Norway (Table 12). Although crop production also removes annually large quantities of these two micro-nutrients, compared to those of the other metals, increase in sludge application from the nation's sludge production density level, 0.10 T DS/ha, to the maximum permissible loading rate, 2 T DS/ha, raises the loading rates of Cu and Zn to such high levels that far exceed their output rates by crop production and leaching, thus making them both become the limiting factors that determine the use of sludge in agriculture. The reason for Cu to give even lower maximum number of years for sludge application than Zn, although its concentration in sludge is lower than that of Zn, is due to its lower permissible concentration limit in the soil and thus lower permissible increase in its concentration in the soil than those of Zn (Table 12). The maximum number of years for sludge application is less than 200 and 500 years, respectively, for Cu and Zn (Table 13).

Opposite to those of Cu, the scale of maximum permissible increase in soil concentration of Cr is very large and the average concentration of Cr in the sludge produced in Norway is very low. These in combination make Cr to be the metal giving the longest duration for sludge application, with a year number based on the nation's average amounting to more than 3,466 (Table 13). Although there are exceptions as will be shown later, in general, chromium is the last metal that limits the use of sludge in agriculture in Norway.

Inclusion of the input from fertilization and atmospheric deposition changes the sequence between Cd and Hg (figure 18). This is due to much higher input of Cd than that of Hg from these two sources. High input of Pb mainly from atmospheric deposition reduces the number of years for sludge application by 360 years. For the other metals, the decrease in number of years due to additional input from other sources is lower than 100 (Table 13).

Table 13. Maximum number of years during which two tons of sludge in dry matter per hectare are annually applied to the soil (Norsk Hydro 1994; SFT Rapport 533:93 1993; Statistics Norway 1994; Vigerust and Wu 1994). (Average for Norway)

	Cd	Pb	Hg	Ni	Zn	Cu	Cr
BAC*	1101	1397	990	842	483	193	3466
BAC plus other sources*	909	1037	926	743	447	190	3262

*: *BAC: Based on background average concentrations of heavy metals in the sludge produced in 1993.*

BAC plus other sources: In addition to BAC, soil heavy metal input from fertilizers and atmospheric deposition further included.

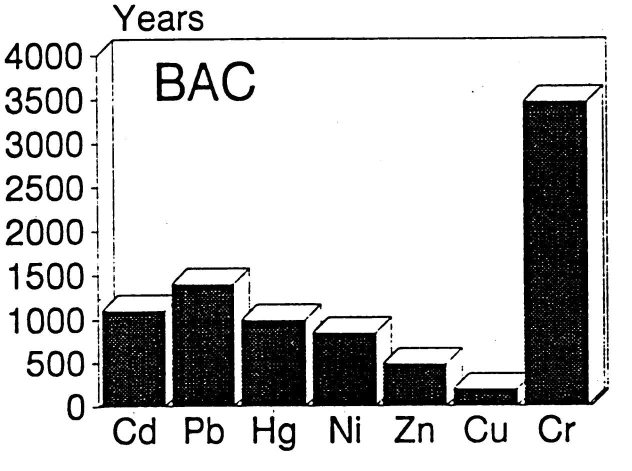
Fig. 18. Maximum number of years during which two tons of sludge in DS per hectare are annually applied to the soil:

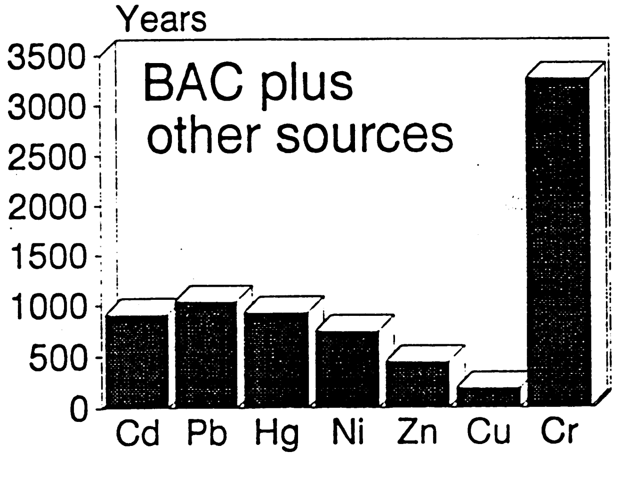
the difference between the maximum permissible concentration and the average concentration of heavy metals in the soil has been used as the upper limit for heavy metal input; and the output by leaching and plant uptake been substracted.

BAC: based on background average concentrations of heavy metals in the sludge.
BAC plus other souces: based on background average concentrations plus input by fertilization and atmospheric deposition.

Norway

(Data sources refer to Table 13)





Østfold

On the county's average, the input rates of Cd, Pb, Hg Cu and Cr from these three sources investigated are higher while those of Ni and particularly Zn are lower than their output rates in Østfold (Figure 19). The difference between soil input and output of Cu, however, is small, compared to those of Cd, Pb, Hg and Cr. In comparison with those nation's average values, the output rates of all heavy metals by plant uptake per unit cultivated area are relatively low in Østfold because of its high cereal but low hay production (Figure 16), and the input rates in this county are relatively high because of its relatively high sludge production density and fertilization intensity, although its input of Cd, Pb and Zn from atmospheric deposition is relatively low (Figures 6, 11 and 14).

The significant increase in Cd input due to high sludge application and fertilization greatly reduces the maximum number of years given by Cd such that Cd becomes the third limiting factor following Cu and Zn (Figure 20). The sequence of maximum number of years for sludge application given by different heavy metals in Østfold is as follows for both BAC (see Equation 2) and BAC plus other sources (see Equation 3):

Cu < Zn < Cd < Pb < Hg < Ni < Cr

Although Cu is still the first limiting factor in Østfold, the maximum number of years given by Cu amounts to more 300 (Table 14), which is higher than the nation's average (Table 13). The concentration of Cu in the sludge produced in Østfold is much lower than that in other counties except for in Vestfold and Vest-Agder (Table 2), which, thus permits higher number of years for sludge application. Since it is the first limiting factor that determines the loading rate and the duration of sludge application, the situation in Østfold with respect to the use of sludge in agriculture is not worse but even better when the nation's average values are used as standards.

Table 14. Maximum number of years during which two tons of sludge in dry matter per hectare are annually applied to the soil (Norsk Hydro 1994; SFT Rapport 533:93 1993; Statistics Norway 1994; Vigerust and Wu 1994). (Østfold)

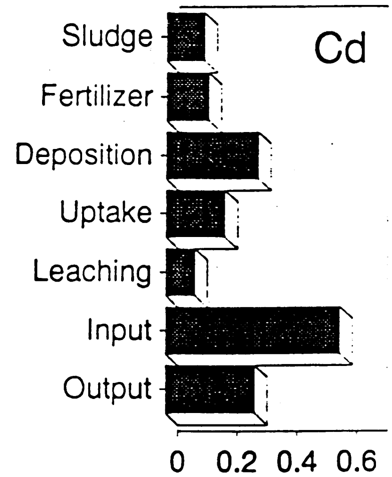
	Cd	Pb	Hg	Ni	Zn	Cu	Cr
BAC*	600	1347	1328	1715	424	343	5202
BAC plus other sources*	501	1068	1215	1555	403	333	4732
BACso* (mg/kg)	0.54	18.5	0.04	10.6	51.3	15.2	28.9

*: *BAC: Based on background average concentrations of heavy metals in the sludge produced in 1993.*
BAC plus other sources: In addition to BAC, soil heavy metal input from fertilizers and atmospheric deposition further included.
BACso: Background average concentrations in the soil estimated for Østfold.

Fig. 19. Soil heavy metal input due to sludge application, fertilization, and atmospheric deposition, and output due to plant uptake and leaching.

Østfold (g/ha/yr)

(Andersson 1992; Norsk Hydro 1994; SFT-rapport 533:93 1993; Statistics Norway 1993; 1994)



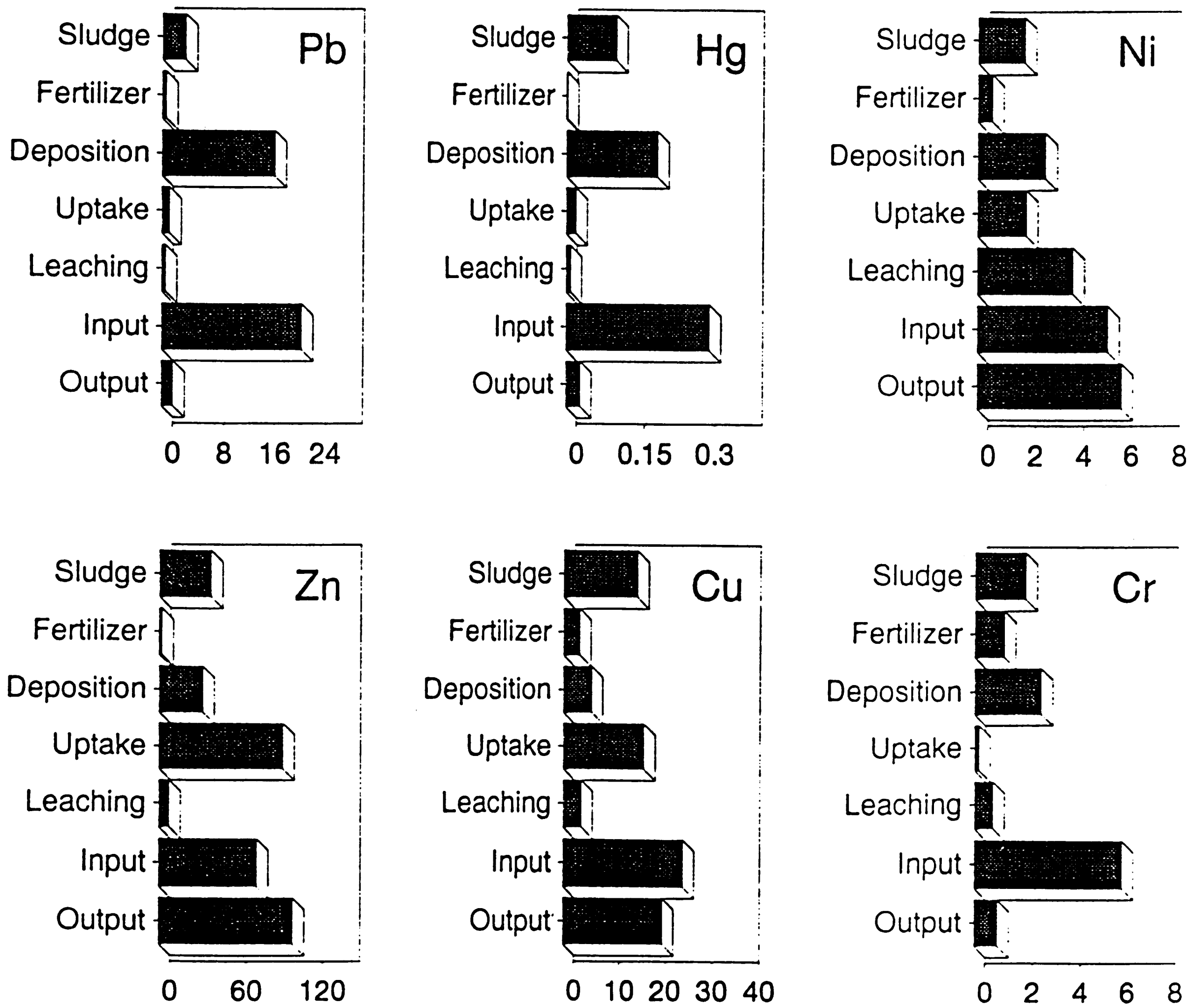


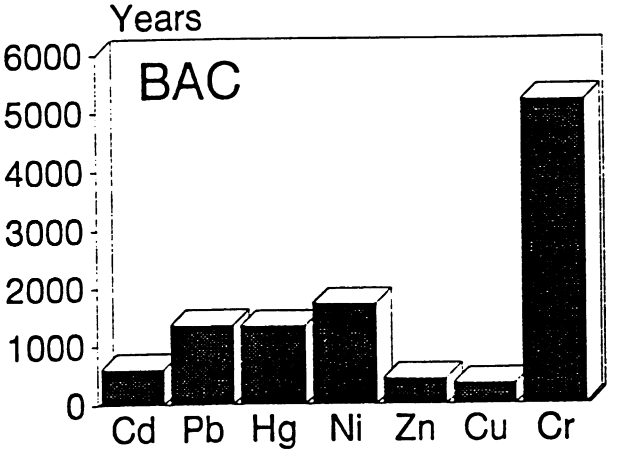
Fig. 20. Maximum number of years during which two tons of sludge in DS per hectare are annually applied to the soil:

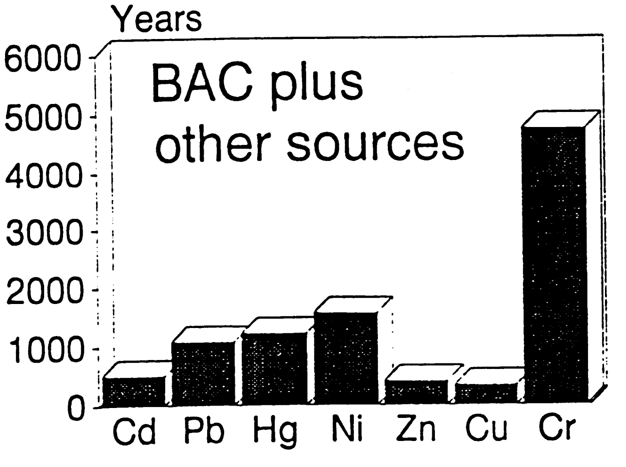
the difference between the maximum permissible concentration and the average concentration of heavy metals in the soil has been used as the upper limit for heavy metal input; and the output by leaching and plant uptake been substracted.

BAC: based on background average concentrations of heavy metals in the sludge.
BAC plus other souces: based on background average concentrations plus input by fertilization and atmospheric deposition.

Østfold

(Data sources refer to Table 14)





Akershus-Oslo

Akershus-Oslo is a region with its input rates of all heavy metals higher than its relevant output rates on the county's average basis (Figure 21). Sludge is shown to be the main source for input of soil Cd, Hg, Ni, Zn, Cu and Cr in this region. This is not only accounted for by its high concentrations of these metals in the sludge (Table 2) but as well its highest sludge production, which, as has been mentioned, contributes up to 36% of the nation's total quantity, and thus gives an extremely high sludge distribution density based on cultivated agricultural areas in this region (Figure 1). The atmospheric deposition generates higher amount of Pb than the sludge while in all cases the fertilizers bring minor amount of heavy metals to the soil (Figure 21).

Copper is still the first liming element in Akershus-Oslo when the sludge loading rate raises to 2 T DS/ha/yr (Figure 22). The order of the maximum number of years for sludge application for both BAC and BAC plus other sources is as follows:

Cu < Zn < Cd < Hg < Ni < Pb < Cr

The reason for Pb and Ni giving higher number of years than Hg is that the average concentrations of Pb and Ni in the soil in Akershus-Oslo are lower than the nation's average (Tables 12 and 15), which gives higher maximum permissible increase in soil concentrations of these two elements and thus allows longer duration for sludge application with the given loading rate. The maximum number of years given by Cu and Zn, is, respectively, 181 and 272 for sludge application, and 178 and 257 for inclusion of other sources in Akershus-Oslo (Table 15), which are the lowest number compared to that in any other counties in Norway. The highest sludge production density in Akershus-Oslo region may bring problem to soil heavy metal contamination in terms of hundred years if all sludge locally produced has to be used in this area. Distributing a certain proportion of sludge produced in Akershus-Oslo to other regions having low sludge production density and particularly low levels of Cu and Zn concentrations in the soil can be one effective solution to minimizing this problem. The essential one, however, is to reduce the cu and Zn concentrations in the sludge.

Table 15. Maximum number of years during which two tons of sludge in dry matter per hectare are annually applied to the soil (Norsk Hydro 1994; SFT Rapport 533:93 1993; Statistics Norway 1994; Vigerust and Wu 1994). (Akershus-Oslo).

	Cd	Pb	Hg	Ni	Zn	Cu	Cr
BAC*	479	1500	909	1048	272	181	2564
BAC plus other sources*	420	1204	855	941	257	178	2430
BACso* (mg/kg)	0.50	12.9	0.04	19.5	95.5	13.8	39.3

*: *BAC: Based on background average concentrations of heavy metals in the sludge produced in 1993.*

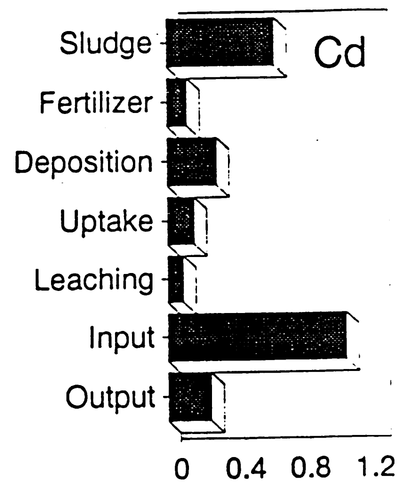
BAC plus other sources: In addition to BAC, soil heavy metal input from fertilizers and atmospheric deposition further included.

BACso: Background average concentrations in the soil estimated for Akershus-Oslo.

Fig. 21. Soil heavy metal input due to sludge application, fertilization, and atmospheric deposition, and output due to plant uptake and leaching.

Akershus-Oslo (g/ha/yr)

(Andersson 1992; Norsk Hydro 1994; SFT-rapport 533:93 1993; Statistics Norway 1993; 1994)



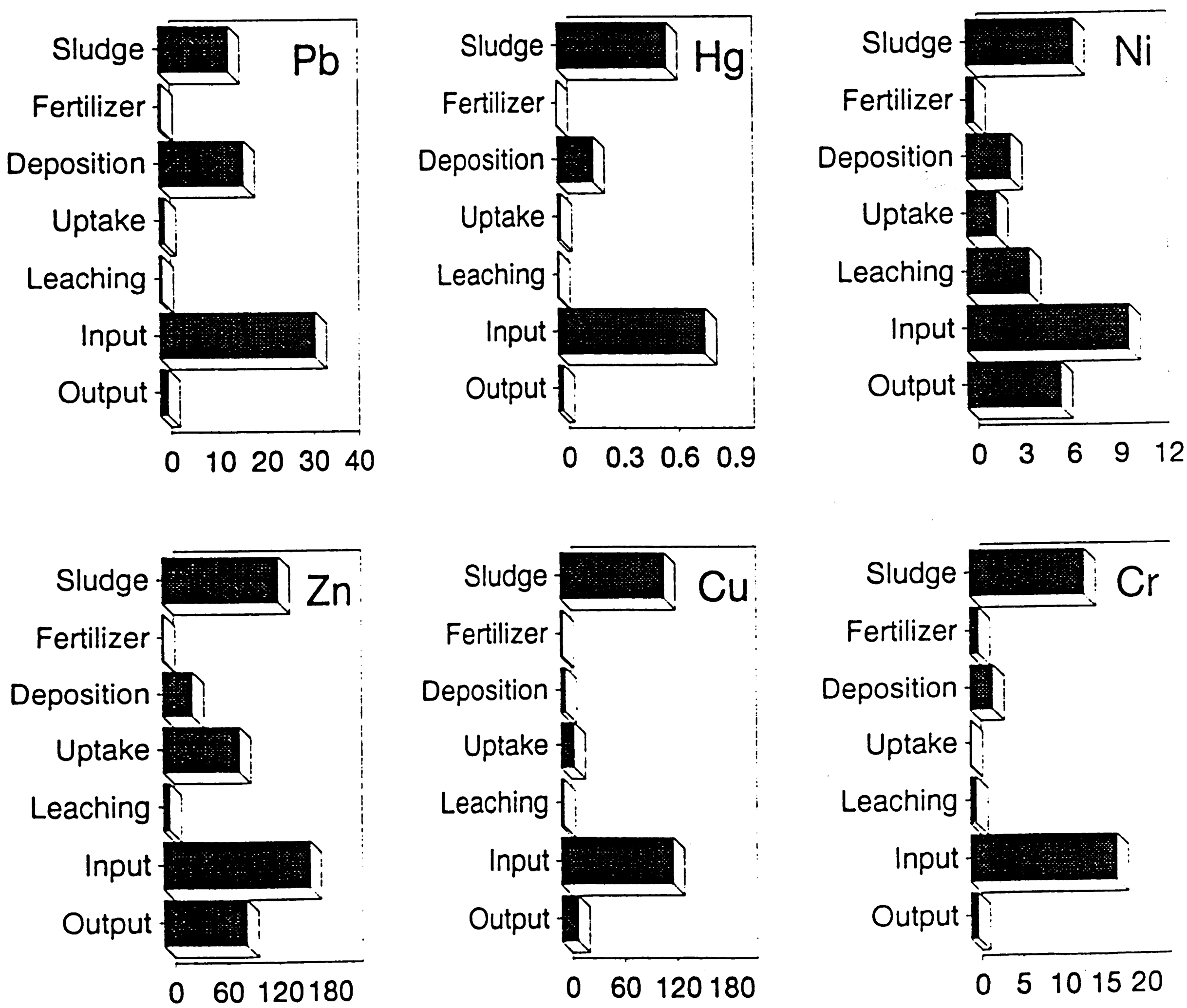


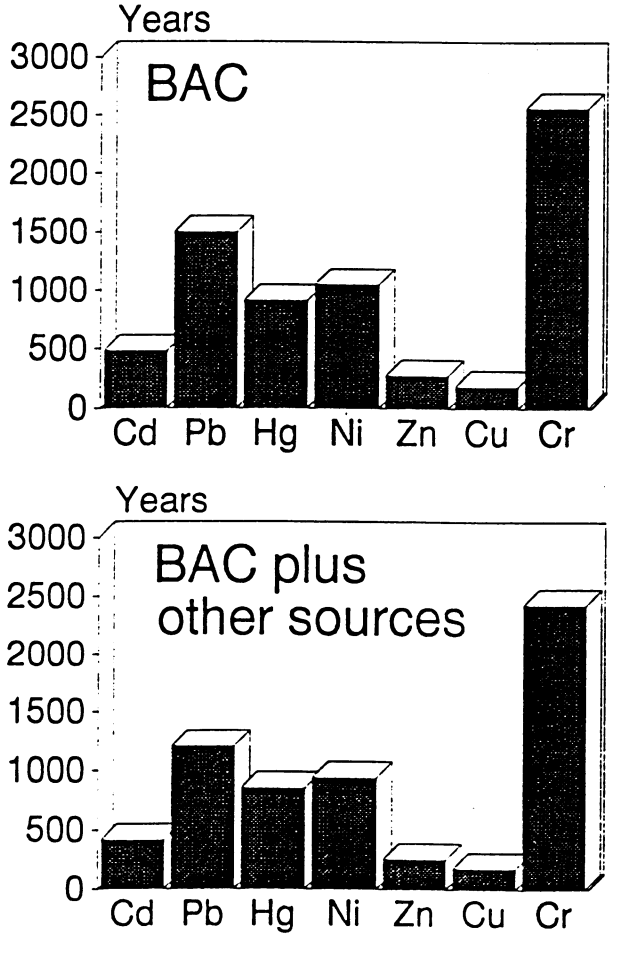
Fig. 22. Maximum number of years during which two tons of sludge in DS per hectare are annually applied to the soil:

the difference between the maximum permissible concentration and the average concentration of heavy metals in the soil has been used as the upper limit for heavy metal input; and the output by leaching and plant uptake been substracted.

BAC: based on background average concentrations of heavy metals in the sludge.
BAC plus other souces: based on background average concentrations plus input by fertilization and atmospheric deposition.

Akershus-Oslo

(Data sources refer to Table 15)



Hedmark

The average concentration of Cd in the sludge produced in Hedmark amounts to 1.8 mg/kg DS, which is the highest value found in Norway. The input of soil Cd from atmospheric deposition is also higher in the this county than the nation's average value. Thus the input rate of Cd in Hedmark is higher than its output rate (Figure 23) although the rate of soil Cd removal by crop production in this county is relatively high. The input of Pb, Hg and Cr is also higher than the output of these three metals, which is mainly due to atmospheric deposition. It can be clearly noticed that the crop production in Hedmark removes more Ni, Zn and Cu from the soil than the county's average input (Figure 23).

As for the maximum number of years for sludge application, there are some significant changes in the order of limitation (Figure 24). The lowest number of years is still associated with Cu but the next lowest, is associated with Cd rather than Zn. Furthermore, just following Cr, Ni gives the second longest duration for sludge application. The order shown in Figure 24 is as follows for both with and without inclusion of other sources:

Cu < Cd < Zn < Hg < Pb < Ni < Cr

Such significant change for Zn is attributed to its low concentration in the soil in this county. The same is true also for Ni. Nevertheless, the number of years for use of sludge in agriculture given by the limiting element, Cu, is higher in Hedmark than the nation's average.

Table 16. Maximum number of years during which two tons of sludge in dry matter per hectare are annually applied to the soil (Norsk Hydro 1994; SFT Rapport 533:93 1993; Statistics Norway 1994; Vigerust and Wu 1994) (Hedmark).

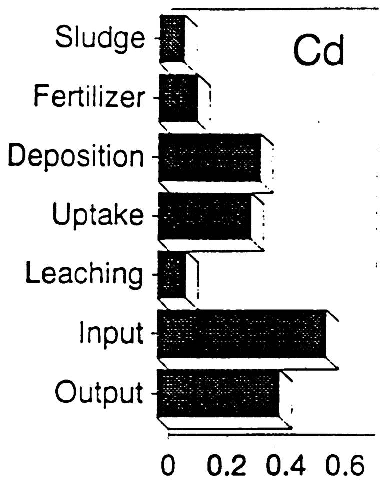
	Cd	Pb	Hg	Ni	Zn	Cu	Cr
BAC*	472	1930	860	2737	817	277	5365
BAC plus other sources*	409	1636	811	2407	752	271	4925
BACso* (mg/kg)	0.50	10.8	0.04	6.8	24.5	12.5	19.8

*: *BAC: Based on background average concentrations of heavy metals in the sludge produced in 1993.*

BAC plus other sources: In addition to BAC, soil heavy metal input from fertilizers and atmospheric deposition further included.

BACso: Background average concentrations in the soil estimated for Hedmark.

Fig. 23. Soil heavy metal input due to sludge application, fertilization, and atmospheric deposition, and output due to plant uptake and leaching.



Hedmark (g/ha/yr)

(Andersson 1992; Norsk Hydro 1994;
SFT-rapport 533:93 1993;
Statistics Norway 1993; 1994)

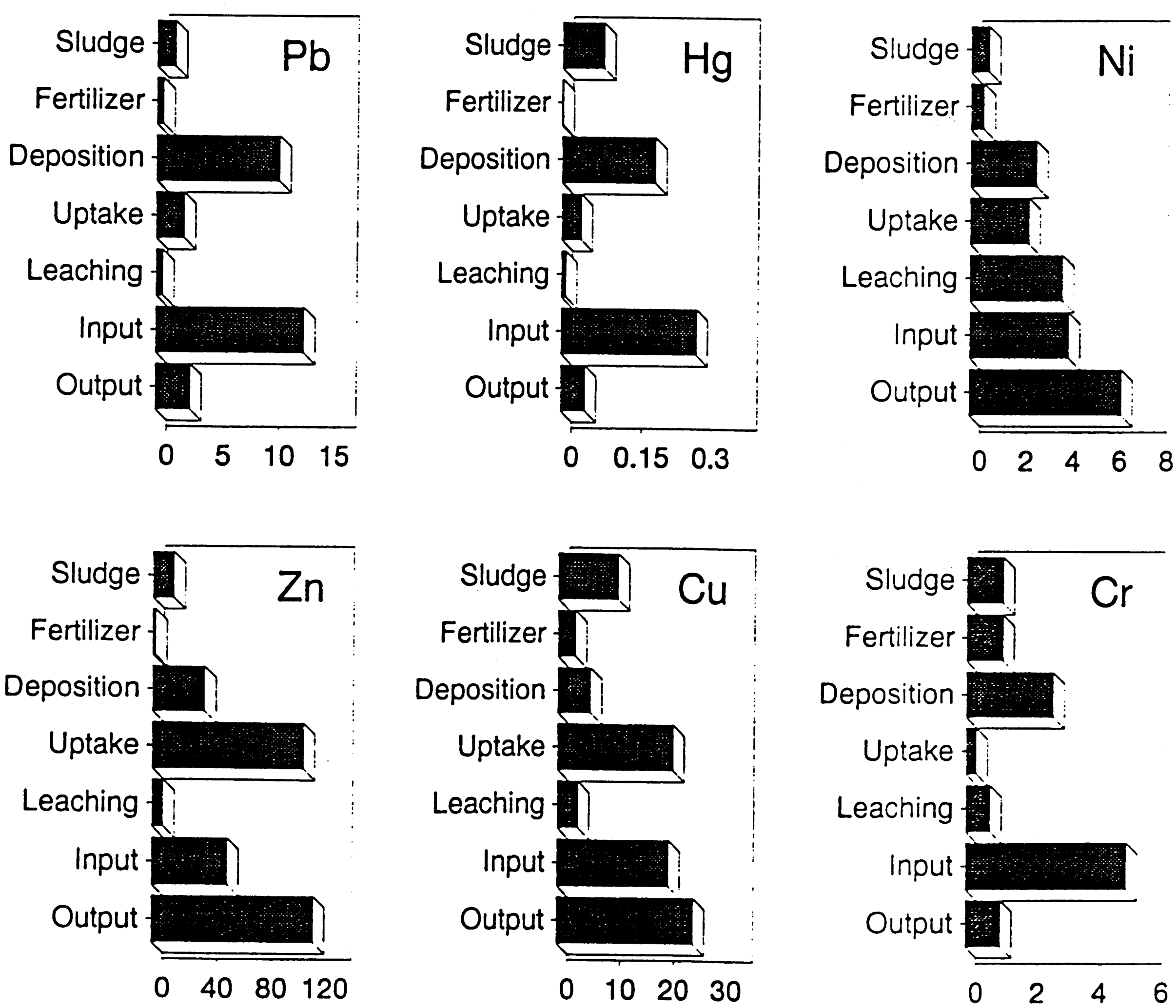


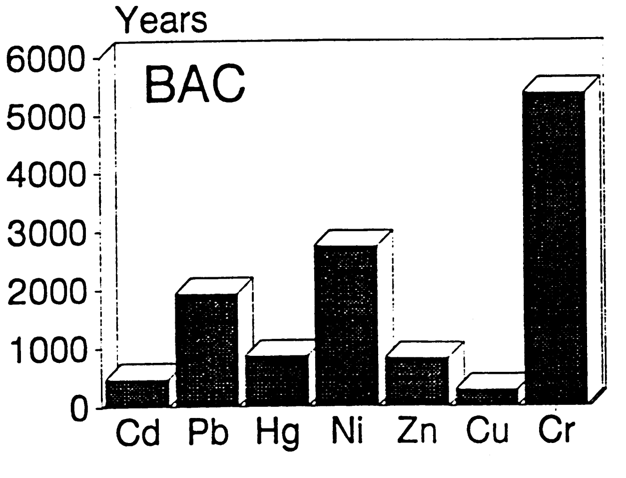
Fig. 24. Maximum number of years during which two tons of sludge in DS per hectare are annually applied to the soil:

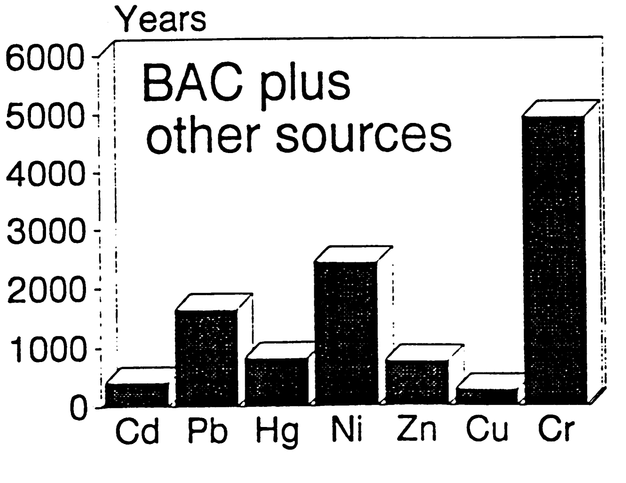
the difference between the maximum permissible concentration and the average concentration of heavy metals in the soil has been used as the upper limit for heavy metal input; and the output by leaching and plant uptake been substracted.

BAC: based on background average concentrations of heavy metals in the sludge.
BAC plus other souces: based on background average concentrations plus input by fertilization and atmospheric deposition.

Hedmark

(Data sources refer to Table 16)





Oppland

Accounted for mainly by their high uptake rates, the average fluxes of Cd and Cu in Oppland are nearly balanced and the input of Ni and Zn in this county is much lower than their output (Figure 25). The low level of Ni in the sludge produced in this county also makes important contribution to the reduction in its soil input rate. The average sludge concentration of Ni in Oppland is 10 mg/kg DS, which is the second lowest value found in Norway (Table 2). The high output rate mainly due to crop uptake does not make significant changes for Pb, Hg and Cr and thus, their input rates still far exceed their output rates in this county (Figure 25).

The order of limitation on sludge application in Oppland is as follows with respect to different heavy metals for both BAC and BAC plus other sources (Figure 26):

Cu < Zn < Hg < Cd < Pb < Cr < Ni

Two interesting cases can be noticed in this sequence: one being Hg, which comes to the third place on limitation, due to extremely high level of this element in the sludge; the other being Ni, which gives a duration for sludge application even longer than Cr, due to, as has been mentioned, extremely low level of this element in the sludge.

Table 17. Maximum number of years during which two tons of sludge in dry matter per hectare are annually applied to the soil (Norsk Hydro 1994; SFT Rapport 533:93 1993; Statistics Norway 1994; Vigerust and Wu 1994) (Oppland).

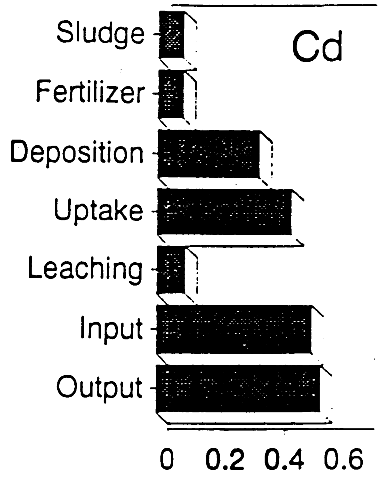
	Cd	Pb	Hg	Ni	Zn	Cu	Cr
BAC*	735	2478	699	4562	646	237	3269
BAC plus other sources*	605	1996	666	3668	599	233	3106
BACso* (mg/kg)	0.53	11.7	0.04	16.9	48.7	22.6	37.2

*: *BAC: Based on background average concentrations of heavy metals in the sludge produced in 1993.*

BAC plus other sources: In addition to BAC, soil heavy metal input from fertilizers and atmospheric deposition further included.

BACso: Background average concentrations in the soil estimated for Oppland.

Fig. 25. Soil heavy metal input due to sludge application, fertilization, and atmospheric deposition, and output due to plant uptake and leaching.



Oppland (g/ha/yr)

(Andersson 1992; Norsk Hydro 1994; SFT-rapport 533:93 1993; Statistics Norway 1993; 1994)

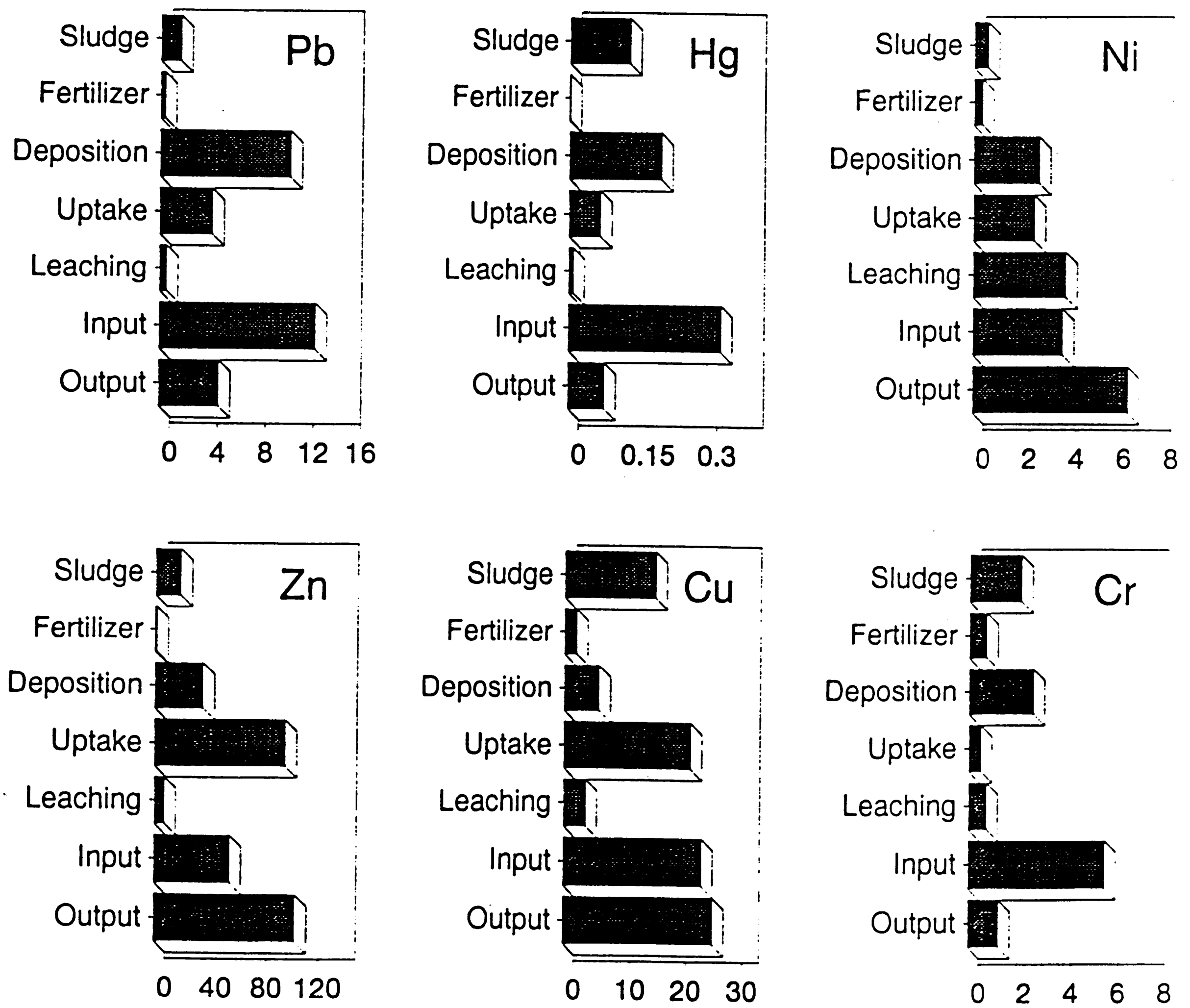


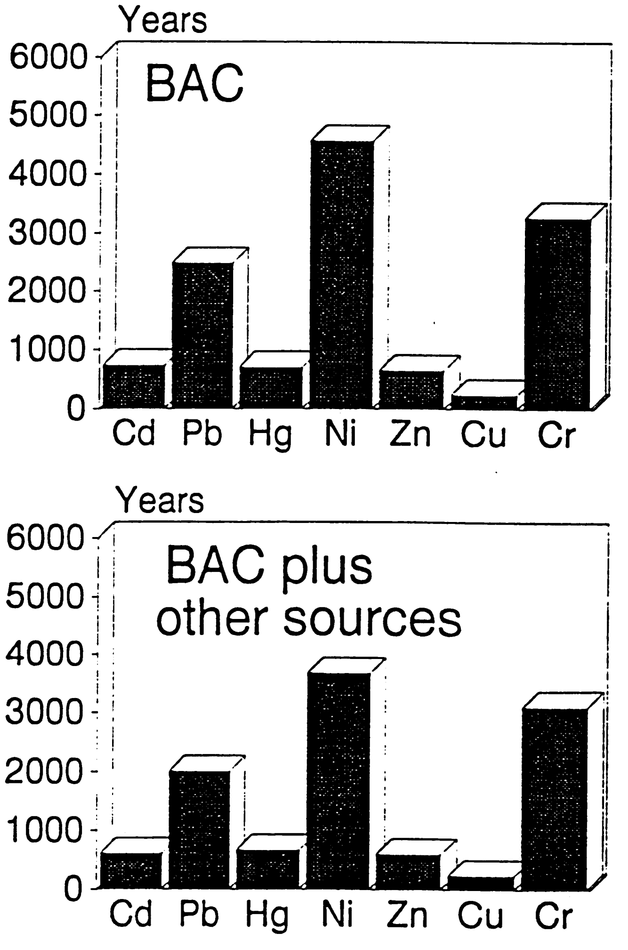
Fig. 26. Maximum number of years during which two tons of sludge in DS per hectare are annually applied to the soil:

the difference between the maximum permissible concentration and the average concentration of heavy metals in the soil has been used as the upper limit for heavy metal input; and the output by leaching and plant uptake been substracted.

BAC: based on background average concentrations of heavy metals in the sludge.
BAC plus other souces: based on background average concentrations plus input by fertilization and atmospheric deposition.

Oppland

(Data sources refer to Table 17)



Buskerud

The soil input in Buskerud is lower than its output for all heavy metals except for Ni (Figure 27). The average concentration of Ni in the sludge is 9 mg/kg DS, which is the lowest as a county's average value found in Norway (Table 2). The removal rates of all heavy metals due to crop production are low in this county, much lower than the nation's average rates (Figure 16), while the Zn concentration in the sludge is very high, amounting to 391 mg/kg (Table 2). Thus, the input of Zn also far exceeds its output although, in general, crop production removes the largest quantity of Zn, compared to that of the other metals, from the soil. The average concentration of Cd in the sludge produced in Buskerud, like that of Ni, is also the lowest, with a value down to 0.8 mg/kg DS (Table 2). The sludge production density in this county, however, is comparably high (Figure 1), which results in a higher input rates for all heavy metals than the nation's average (Figure 6).

The order of maximum number of years for sludge application shown in Figure 28 is as follows for BAC:

Cu < Zn < Cd < Hg < Pb < Cr < Ni

and for BAC plus other sources:

Cu < Zn < Cd < Hg < Pb < Ni < Cr

The inclusion of the input from atmospheric deposition and fertilization changes the order between Ni and Cr and also reduces the number of years for Cd by 300 (Table 18).

Table 18. Maximum number of years during which two tons of sludge in dry matter per hectare are annually applied to the soil (Norsk Hydro 1994; SFT Rapport 533:93 1993; Statistics Norway 1994; Vigerust and Wu 1994). (Buskerud).

	Cd	Pb	Hg	Ni	Zn	Cu	Cr
BAC*	1190	1558	1222	5041	399	242	5038
BAC plus other sources*	869	1332	1126	3958	378	237	4685
BACso* (mg/kg)	0.50	15.0	0.04	9.3	56.8	17.6	21.2

**: BAC: Based on background average concentrations of heavy metals in the sludge produced in 1993.*

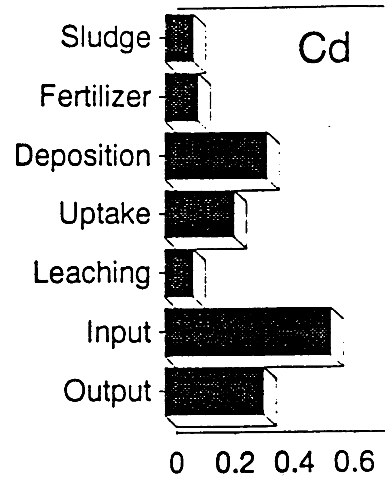
BAC plus other sources: In addition to BAC, soil heavy metal input from fertilizers and atmospheric deposition further included.

BACso: Background average concentrations in the soil estimated for Buskerud.

Fig. 27. Soil heavy metal input due to sludge application, fertilization, and atmospheric deposition, and output due to plant uptake and leaching.

Buskerud (g/ha/yr)

(Andersson 1992; Norsk Hydro 1994; SFT-rapport 533:93 1993; Statistics Norway 1993; 1994)



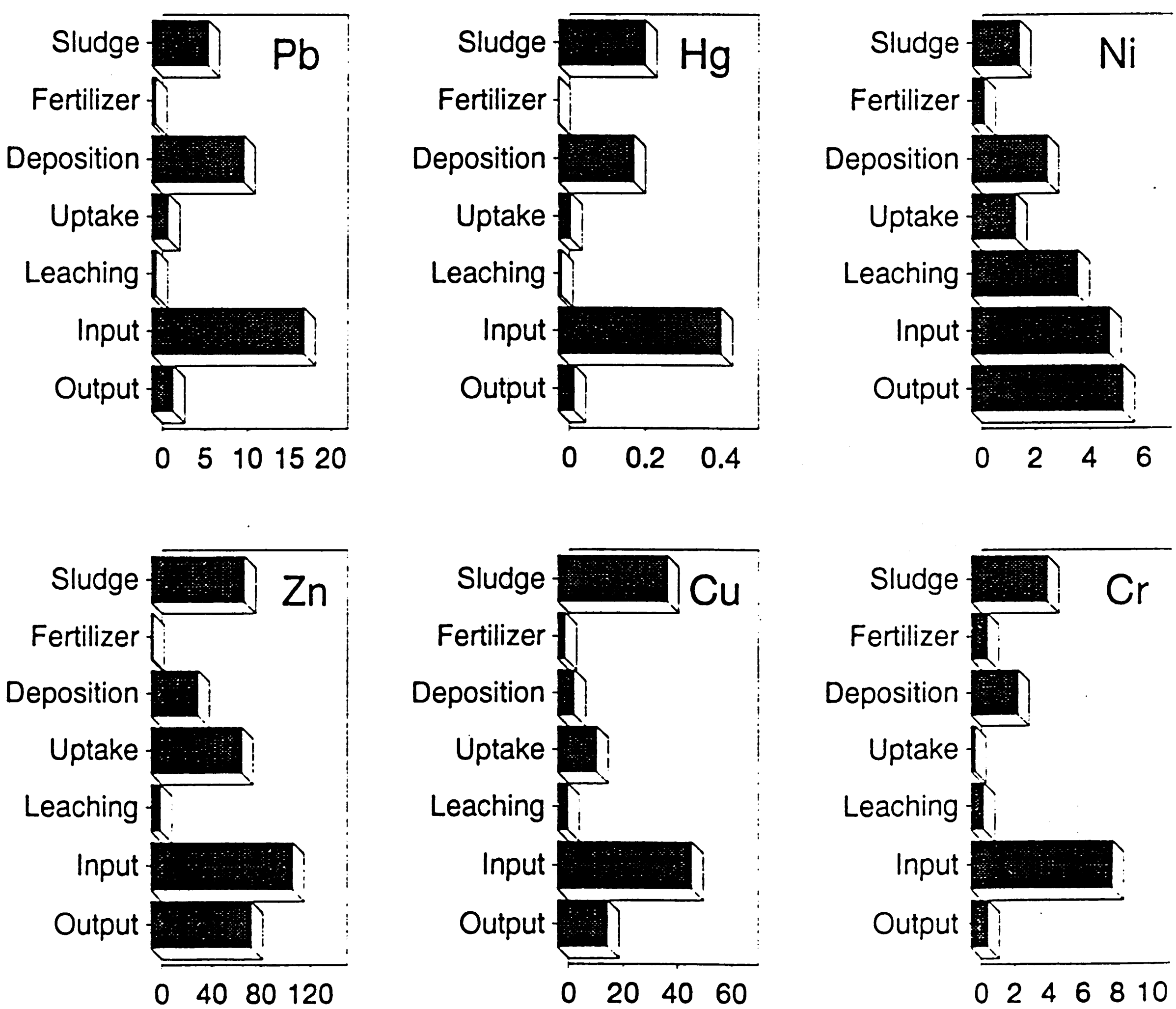


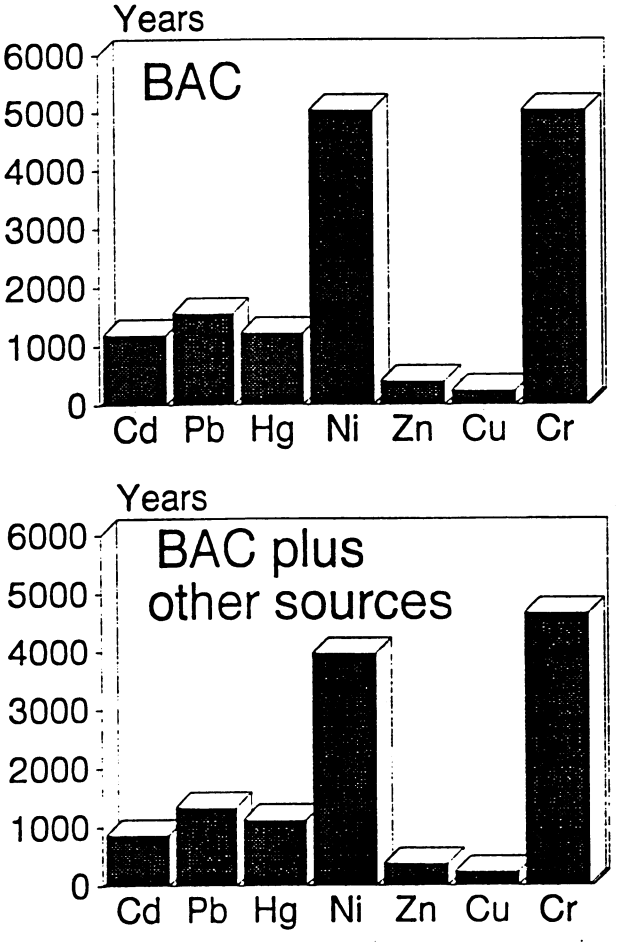
Fig. 28. Maximum number of years during which two tons of sludge in DS per hectare are annually applied to the soil:

the difference between the maximum permissible concentration and the average concentration of heavy metals in the soil has been used as the upper limit for heavy metal input; and the output by leaching and plant uptake been substracted.

BAC: based on background average concentrations of heavy metals in the sludge.
BAC plus other souces: based on background average concentrations plus input by fertilization and atmospheric deposition.

Buskerud

(Data sources refer to Table 18)



Vestfold

The input rates of Cd, Pb, Hg, Cu and Cr all exceed their output rates in Vestfold while the fluxes of Ni and Zn are approximately balanced (Figure 29). The sludge production density and the input of metals from atmospheric deposition are comparably low in this county but its metal input rates from fertilizers is the highest in Norway. Fertilization normally has an effect on soil Cd input. This effect, however, is largely counteracted by the low Cd concentration in the sludge in this county (Table 2). The average Cd çoncentration in sludge is the lowest in Vestfold as that is in Buskerud. On the other hands, however, the output rates of metals due to crop production in Vestfold are also the lowest in Norway (Figure 16).

The maximum number of years for sludge application in Vestfold is following the order for both BAC and BAC plus other sources (Figure 30):

Zn < Cu < Pb < Cd < Hg < Ni < Cr

Zinc becomes the first limiting element in Vestfold simply because of its extremely high level in both sludge and soil (Tables 2 and 19). The average concentration of Zn in sludge amounts to 519 mg/kg DS (Table 2), which is the highest found among all counties in Norway. The Pb concentration in sludge in Vestfold, 42 mg/kg DS, is also the highest in Norway, which leads Pb into the third place in the order of limitation on sludge application (Figure 30).

Table 19. Maximum number of years during which two tons of sludge in dry matter per hectare are annually applied to the soil (Norsk Hydro 1994; SFT Rapport 533:93 1993; Statistics Norway 1994; Vigerust and Wu 1994) (Vestfold).

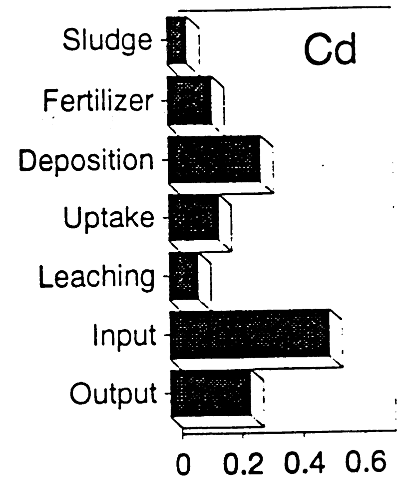
	Cd	Pb	Hg	Ni	Zn	Cu	Cr
BAC*	1128	931	1326	2297	200	445	6694
BAC plus other sources*	838	761	1213	1986	192	428	5862
BACso* (mg/kg)	0.50	24.4	0.04	12.8	86.5	11.8	35.2

*: *BAC: Based on background average concentrations of heavy metals in the sludge produced in 1993.*
BAC plus other sources: In addition to BAC, soil heavy metal input from fertilizers and atmospheric deposition further included.
BACso: Background average concentrations in the soil estimated for Vestfold.

Fig. 29. Soil heavy metal input due to sludge application, fertilization, and atmospheric deposition, and output due to plant uptake and leaching.

Vestfold (g/ha/yr)

(Andersson 1992; Norsk Hydro 1994; SFT-rapport 533:93 1993; Statistics Norway 1993; 1994)



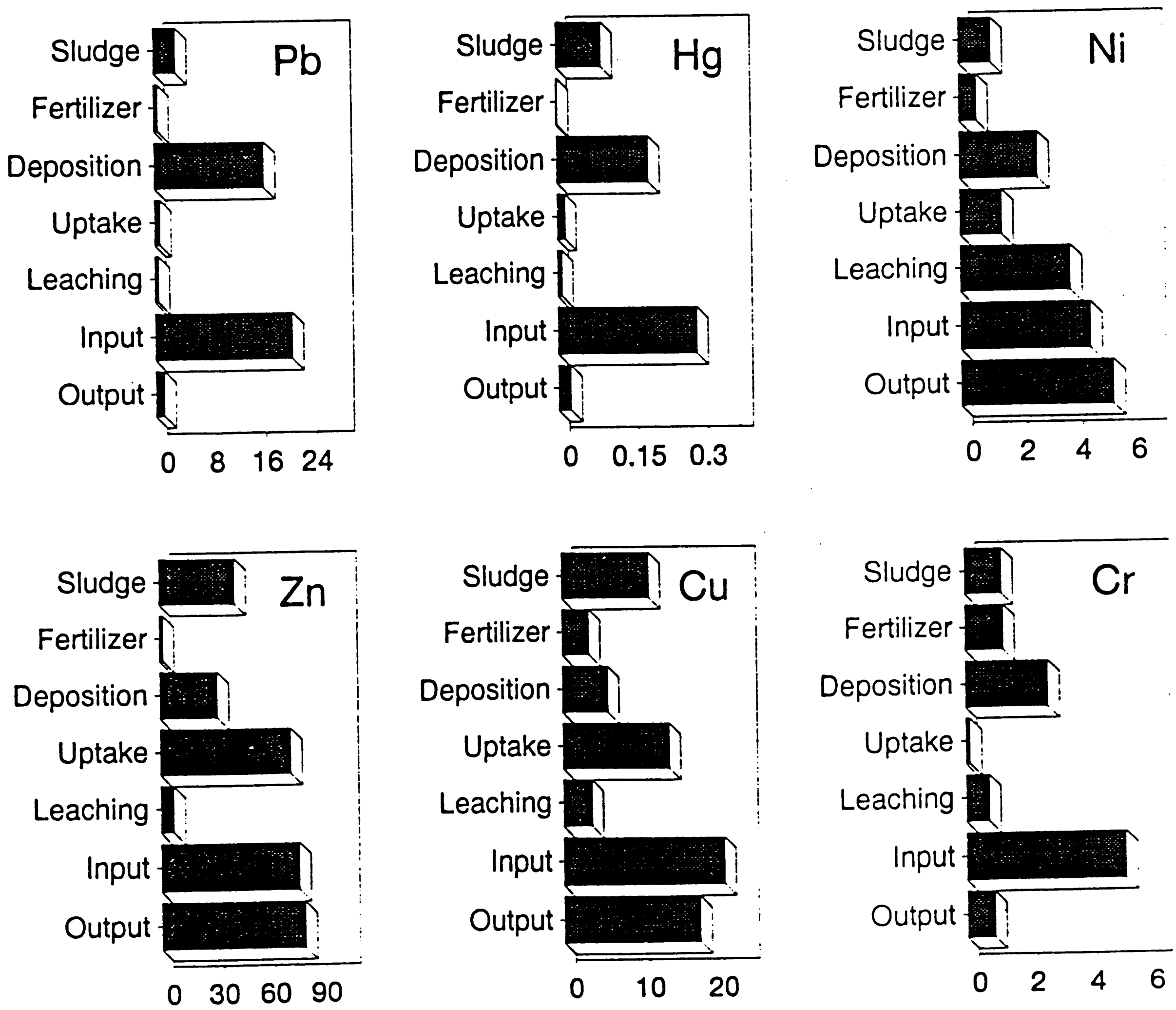


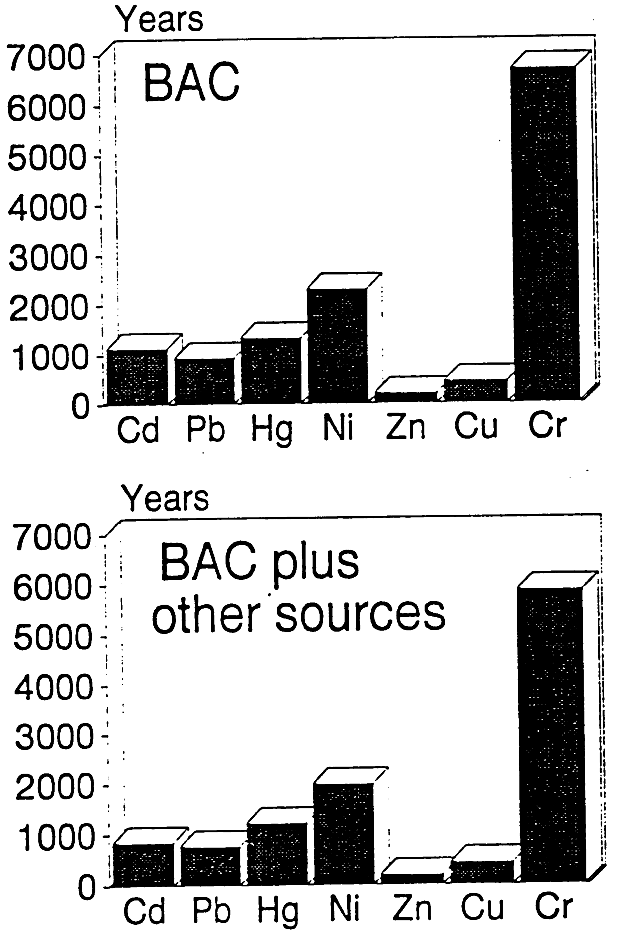
Fig. 30. Maximum number of years during which two tons of sludge in DS per hectare are annually applied to the soil:

the difference between the maximum permissible concentration and the average concentration of heavy metals in the soil has been used as the upper limit for heavy metal input; and the output by leaching and plant uptake been substracted.

BAC: based on background average concentrations of heavy metals in the sludge.
BAC plus other souces: based on background average concentrations plus input by fertilization and atmospheric deposition.

Vestfold

(Data sources refer to Table 19)



Telemark

The input rates of all seven heavy metals are higher than their output rates in Telemark (Figure 31), which is mainly due to their relatively high levels of metal input from sludge and atmospheric deposition and low levels of metal removal by plant uptake. The sludge concentrations of Pb, Cu and Cr are very high in this county while those of Hg and Ni are the highest in the country (Table 2), which apparently contribute to the soil heavy metal input in this county.

The order of the maximum number of years for sludge application in Telemark is as follow for BAC:

Cu < Zn < Cd < Hg < Pb < Ni < Cr

and for BAC plus other sources:

Cu < Cd < Zn < Hg < Pb < Ni < Cr

The input from atmospheric deposition and fertilization reduces the number of years given by Cd by approximately 100 such that Cd becomes the second limiting factor in Telemark (Table 20). Although Ni stands in the second last place in terms of limitation on use of sludge in agriculture, the maximum number of years given by Ni is relatively low due to its high sludge concentration.

Table 20. Maximum number of years during which two tons of sludge in dry matter per hectare are annually applied to the soil (Norsk Hydro 1994; SFT Rapport 533:93 1993; Statistics Norway 1994; Vigerust and Wu 1994) (Telemark).

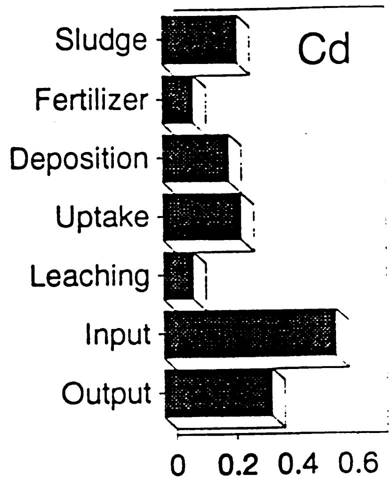
	Cd	Pb	Hg	Ni	Zn	Cu	Cr
BAC*	706	1284	811	1332	696	250	2119
BAC plus other sources*	609	1013	767	1226	639	245	2047
BACso* (mg/kg)	0.52	17.0	0.04	13.0	38.4	11.3	25.9

*: *BAC: Based on background average concentrations of heavy metals in the sludge produced in 1993.*
BAC plus other sources: In addition to BAC, soil heavy metal input from fertilizers and atmospheric deposition further included.
BACso: Background average concentrations in the soil estimated for Telemark.

Fig. 31. Soil heavy metal input due to sludge application, fertilization, and atmospheric deposition, and output due to plant uptake and leaching.

Telemark (g/ha/yr)

(Andersson 1992; Norsk Hydro 1994; SFT-rapport 533:93 1993; Statistics Norway 1993; 1994)



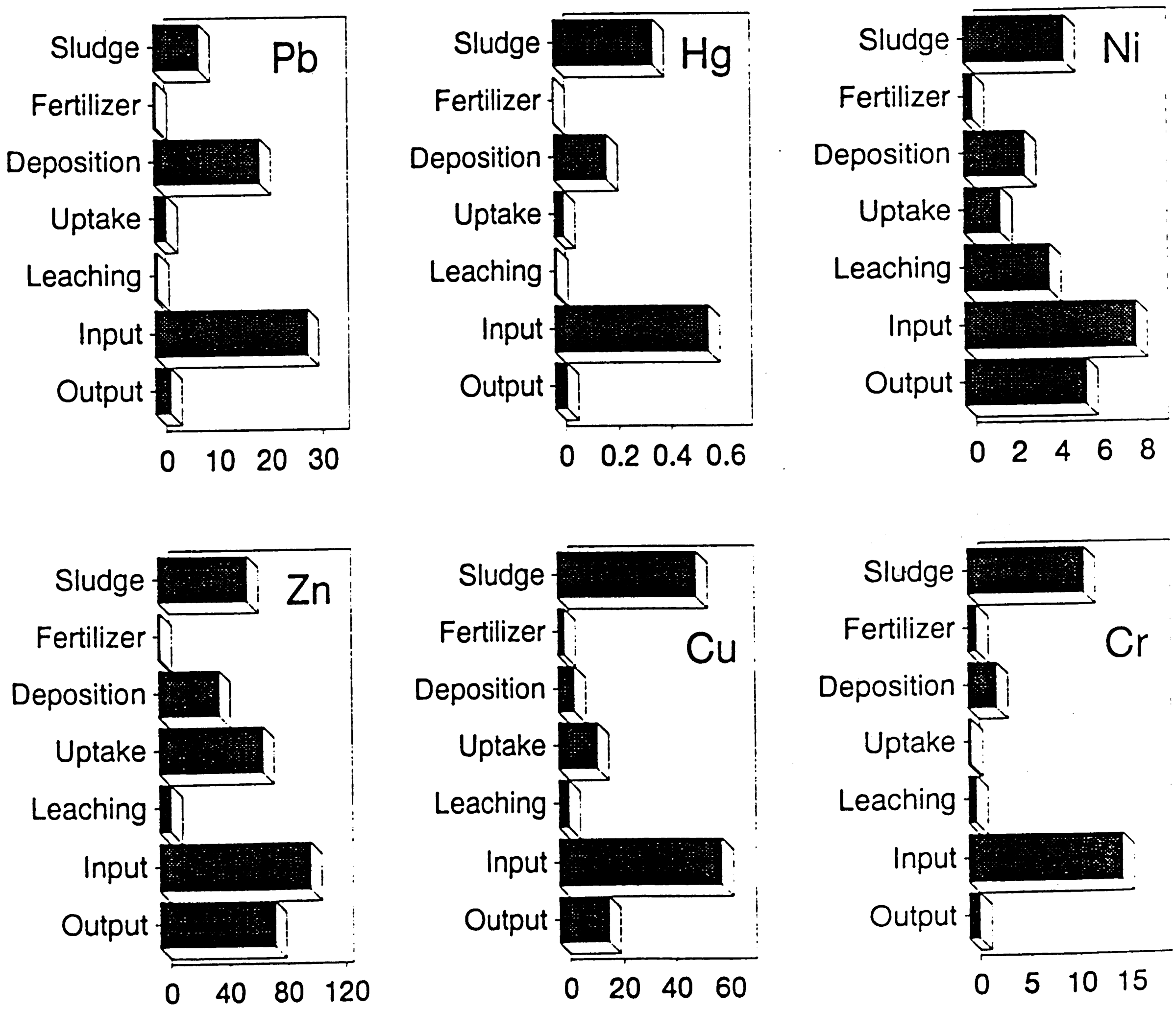


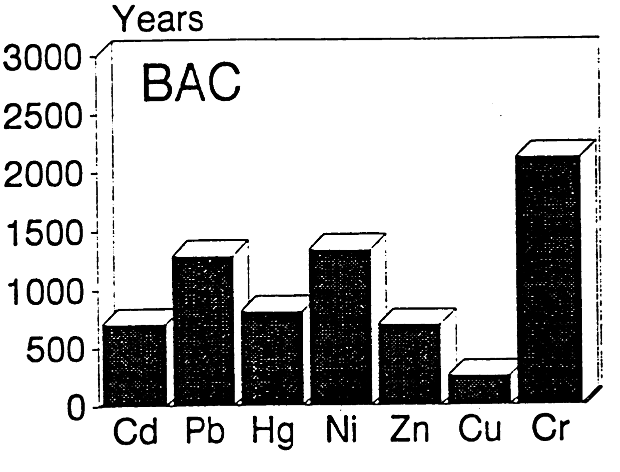
Fig. 32. Maximum number of years during which two tons of sludge in DS per hectare are annually applied to the soil:

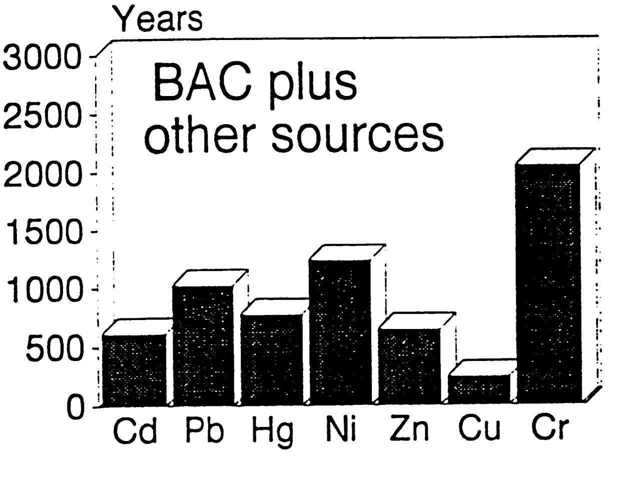
the difference between the maximum permissible concentration and the average concentration of heavy metals in the soil has been used as the upper limit for heavy metal input; and the output by leaching and plant uptake been substracted.

BAC: based on background average concentrations of heavy metals in the sludge.
BAC plus other souces: based on background average concentrations plus input by fertilization and atmospheric deposition.

Telemark

(Data sources refer to Table 20)





Aust-Agder

The soil input rates of heavy metals in Aust-Agder are all higher than their output rates except for that of Ni (Figure 33). The major source for soil heavy metal influxes in this county is the atmospheric deposition with that of Cr as an exception. As has been shown in Table 2, Aust-Agder has the lowest sludge concentrations of Cd, Pb, and Hg but the highest sludge concentration of Cr, which gives much lower levels of Cd, Pb and Hg input rates but much higher level of Cr input rate from sludge application than those from atmospheric deposition (Figure 33).

The two micro-nutrients, Cu and Zn are still the limiting factors in Aust-Agder (Figure 34), followed by the other metals in their maximum number of years for sludge application in the sequence for BAC:

Cu < Zn < Cd < Pb < Hg < Cr < Ni

and for BAC plus other sources:

Cu < Zn < Pb < Cd < Hg < Cr < Ni

When the input from atmospheric deposition and fertilization are not excluded, Cd is in the third limiting factor, which is due to its relatively high concentration in the soil (Table 21). In both cases, BAC and BAC plus other sources, Ni gives the longest duration for sludge application mainly due to its extremely low level in the soil in this county (Table 21). Atmospheric deposition has a great influence on soil metal input in this area. Accounted for by this influence, the positions of Cd and Pb are reversed in the order of limitation to the use of sludge in agricultural recycling (Figure 34).

Table 21. Maximum number of years during which two tons of sludge in dry matter per hectare are annually applied to the soil (Norsk Hydro 1994; SFT Rapport 533:93 1993; Statistics Norway 1994; Vigerust and Wu 1994) (Aust-Agder).

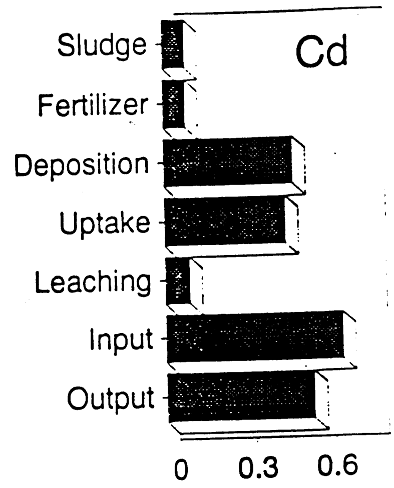
	Cd	Pb	Hg	Ni	Zn	Cu	Cr
BAC*	1220	1569	1900	2865	579	222	2024
BAC plus other sources*	824	695	1677	2524	519	218	1963
BACso* (mg/kg)	0.56	33.8	0.04	5.28	29.2	15.0	21.3

*: *BAC: Based on background average concentrations of heavy metals in the sludge produced in 1993.*
BAC plus other sources: In addition to BAC, soil heavy metal input from fertilizers and atmospheric deposition further included.
BACso: Background average concentrations in the soil estimated for Aust-Agder.

Fig. 33. Soil heavy metal input due to sludge application, fertilization, and atmospheric deposition, and output due to plant uptake and leaching.

Aust-Agder (g/ha/yr)

(Andersson 1992; Norsk Hydro 1994; SFT-rapport 533:93 1993; Statistics Norway 1993; 1994)



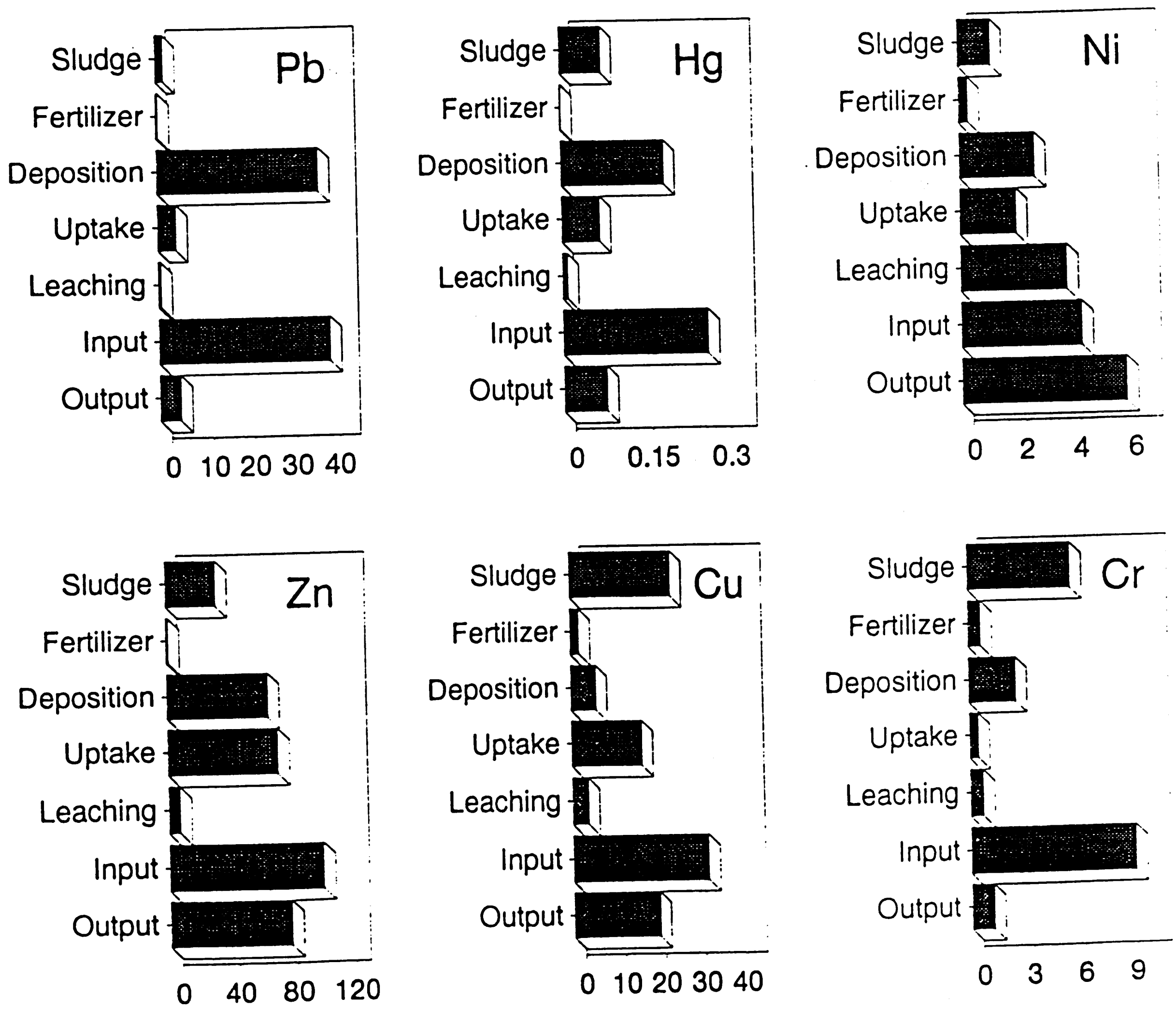


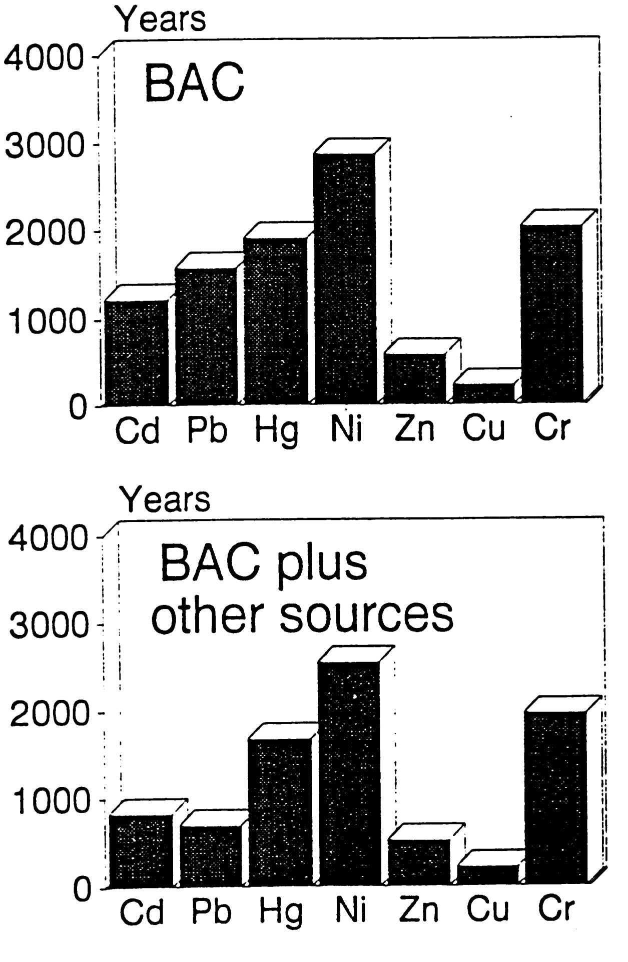
Fig. 34. Maximum number of years during which two tons of sludge in DS per hectare are annually applied to the soil:

the difference between the maximum permissible concentration and the average concentration of heavy metals in the soil has been used as the upper limit for heavy metal input; and the output by leaching and plant uptake been substracted.

BAC: based on background average concentrations of heavy metals in the sludge.
BAC plus other souces: based on background average concentrations plus input by fertilization and atmospheric deposition.

Aust-Agder

(Data sources refer to Table 21)



Vest-Agder

The input rates of all seven heavy metals in Vest-Agder are higher than their output rates (Figure 35). This is mainly due to the highest sludge production density based on cultivated areas (Figure 1) and the highest atmospheric input (Figure 14) in this county. Vest-Agder has the lowest concentrations of Cu and Cr in the sludge (Table 2) and thus, their input rates from sludge are relatively low despite of the highest sludge production density in this county.

The extremely low level of Cu in both sludge and soil in Vest-Agder gives a maximum number of years for sludge application for this element to above 1000 years (Table 22). Thus Zn becomes the first limiting factor in this county (Figure 36) with a sequence for BAC:

Zn < Cd < Cu < Hg < Pb < Ni < Cr

and for BAC plus other sources:

Zn < Pb < Cd < Hg < Cu < Ni < Cr

In contrast to that in Vestfold, where Zn is also the first liming element due to its extremely high concentration in both sludge and soil, Zn concentration in the sludge produced in Vest-Agder is close to the nation's average value while its concentration in the soil is relatively low, thus giving a number of years for sludge application as 601 and 539, respectively (Table 22), which are the highest numbers among the lowest maximum numbers of years for sludge application in all the listed counties in Norway. In other words, it can also be regarded as that the low concentration of Cu in the sludge has promoted the use of sludge in agriculture, and thus, as an example showing the high importance in reducing the concentration of the limiting element in sludge.

Table 22. Maximum number of years during which two tons of sludge in dry matter per hectare are annually applied to the soil (Norsk Hydro 1994; SFT Rapport 533:93 1993; Statistics Norway 1994; Vigerust and Wu 1994) (Vest-Agder).

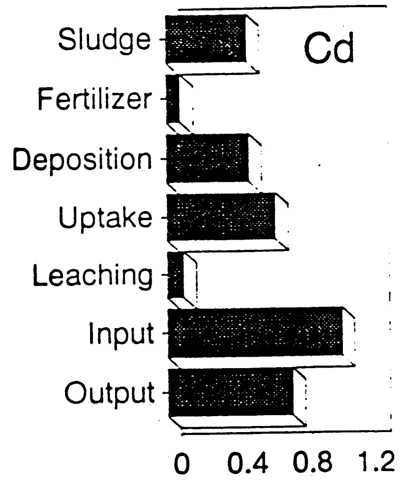
	Cd	Pb	Hg	Ni	Zn	Cu	Cr
BAC*	896	1402	1195	3211	601	1174	10061
BAC plus other sources*	637	597	1073	2824	539	1082	8782
BACso* (mg/kg)	0.57	36.5	0.04	3.33	26.2	11.4	18.1

*: *BAC: Based on background average concentrations of heavy metals in the sludge produced in 1993.*
BAC plus other sources: In addition to BAC, soil heavy metal input from fertilizers and atmospheric deposition further included.
BACso: Background average concentrations in the soil estimated for Vest-Agder.

Fig. 35. Soil heavy metal input due to sludge application, fertilization, and atmospheric deposition, and output due to plant uptake and leaching.

Vest-Agder (g/ha/yr)

(Andersson 1992; Norsk Hydro 1994; SFT-rapport 533:93 1993; Statistics Norway 1993; 1994)



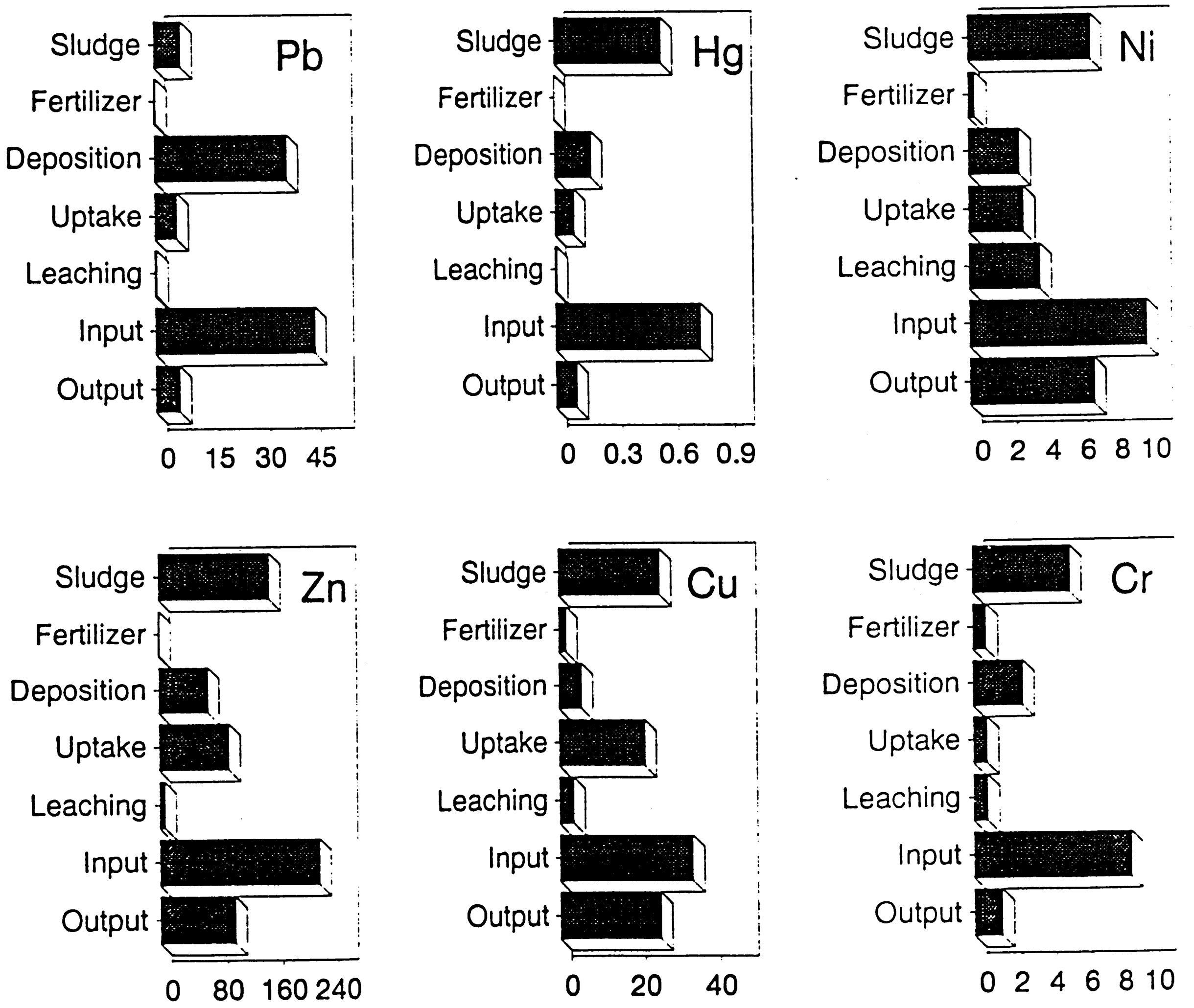


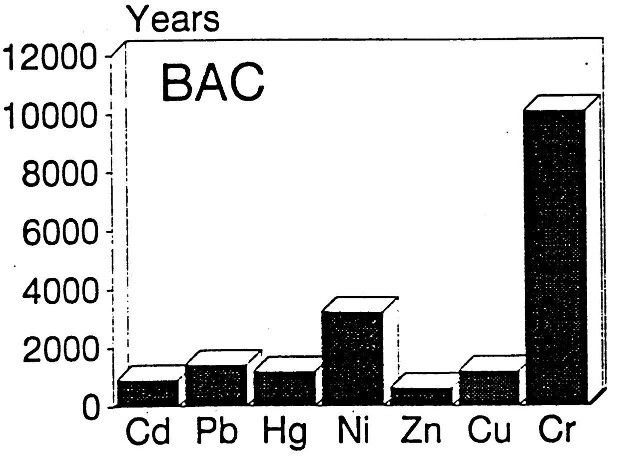
Fig. 36. Maximum number of years during which two tons of sludge in DS per hectare are annually applied to the soil:

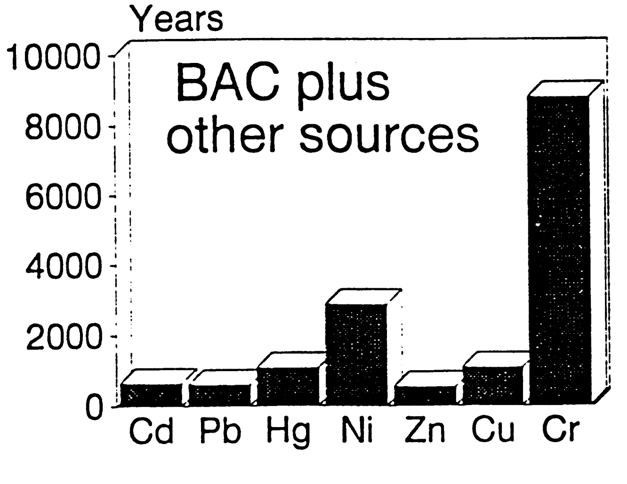
the difference between the maximum permissible concentration and the average concentration of heavy metals in the soil has been used as the upper limit for heavy metal input; and the output by leaching and plant uptake been substracted.

BAC: based on background average concentrations of heavy metals in the sludge.
BAC plus other souces: based on background average concentrations plus input by fertilization and atmospheric deposition.

Vest-Agder

(Data sources refer to Table 22)





The other counties

Because of lowest sludge production density and highest heavy metal uptake due to high feed and fodder production, the average soil input rates of Cd, Pb, Ni, Zn and Cu in the other counties are all lower than their soil output rates (Figure 37). The remaining two metals, Hg and Cr, have higher input than output mainly due to atmospheric deposition. As use of sludge in agricultural recycling has been rarely practised in these counties, the maximum permissible number of years for sludge application has not been calculated for these counties.

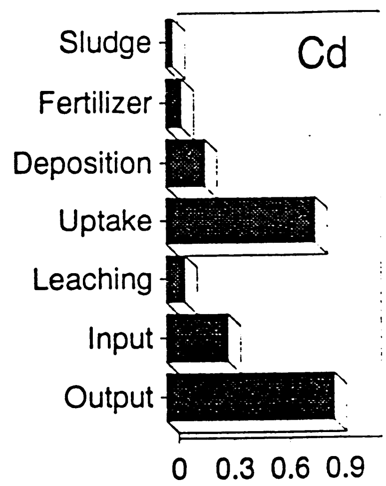
The limiting metals: Cu and Zn

The lowest maximum number of years for sludge application with a loading rate, 2 T DS/ha, either excluding or including the input of heavy metals from fertilization and atmospheric deposition are either associated with Cu or associated with Zn in different counties of Norway. The differences among the lowest numbers found in respective counties, using BAC plus other sources defined by Equations 3 and 5 as an example, are compared in Figure 38. The shortest duration for sludge application in Akershus-Oslo limited by Cu and the next shortest, in Vestfold limited by Zn show clearly that the concentrations of Cu and Zn are the limiting factors determining the use of sludge in agricultural recycling in Norway. Aimed at promoting the correct use of sludge, further reduction of the concentrations of Cu and Zn in relevant sewage treatment systems should be the most important task in the coming future in Norway.

Fig. 37. Soil heavy metal input due to sludge application, fertilization, and atmospheric deposition, and output due to plant uptake and leaching.

Other Counties (g/ha/yr)

(Andersson 1992; Norsk Hydro 1994; SFT-rapport 533:93 1993; Statistics Norway 1993; 1994)



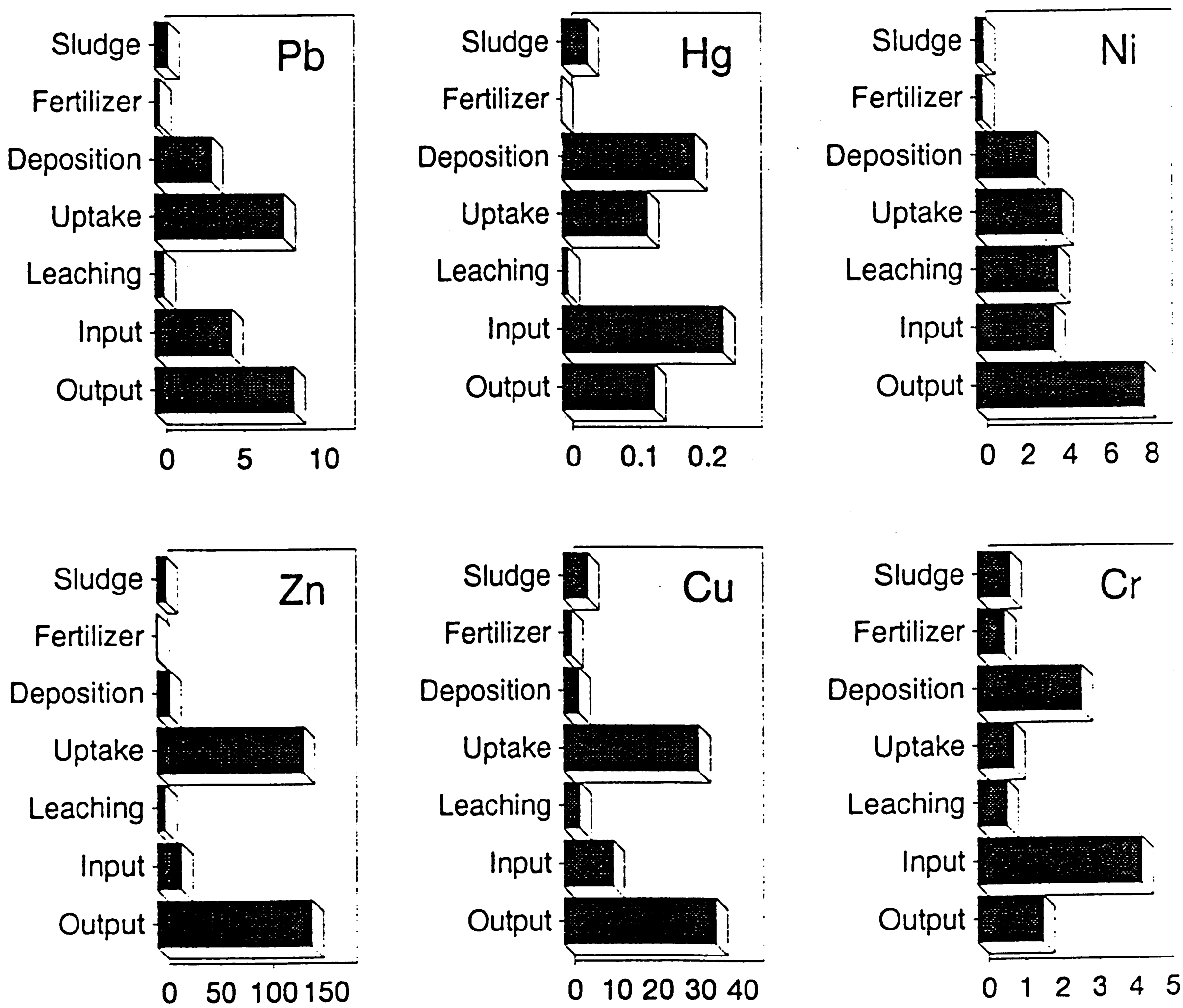
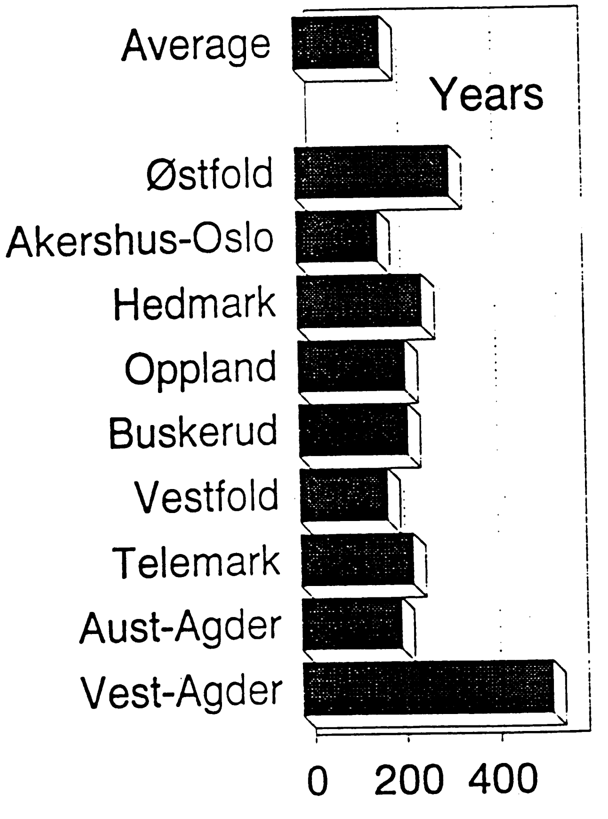


Fig. 38. The maximum number of years for sludge application with an annual loading rate of 2 T DS/ha determined by the maximum permissible concentrations of Cu (for the average, Østfold, Akershus-Oslo, Hedmark, Oppland, Buskerud, Telemark and Aust-Agder) and Zn (for Vestfold and Vest-Agder) in the soil according to the regulations legislated in Norway.



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Appendix

1. Data for Figure 1. Annual sludge production and distribution in different counties of Norway (Aquateam Norway 1994; Statistics Norway 1993; 1994).

County	Sludge produc. (1000 T DS)	Agric. area (1000 ha)	Cultiv. area (1000 ha)	Vegetable area (1000 ha)	Area for use of sludge (1000 ha)	sludge/ hectare (T DS/ha)
Total	88.69	1033.90	883.09	5.94	877.15	.10
Østfold	7.70	78.86	76.92	0.49	76.43	.10
Akershus-Oslo	32.00	83.57	81.30	0.26	81.04	.39
Hedmark	5.41	108.51	104.31	0.77	103.54	.05
Oppland	6.90	97.87	88.11	0.39	87.72	.08
Buskerud	9.16	52.12	48.20	0.67	47.53	.19
Vestfold	3.68	44.61	43.83	1.45	42.38	.09
Telemark	5.05	25.70	23.31	0.10	23.21	.22
Aust-Agder	1.08	11.64	10.83	0.30	10.53	.10
Vest-Agder	6.66	19.20	15.39	0.15	15.24	.44
Others	13.00	511.82	390.89	1.36	389.53	.03

2. Data for Figure 2. Average concentrations of heavy metals in the sludge produced in different years in Norway (Aquateam Norway 1994; SFT-rapport nr. 93:26 1993; Statistics Norway 1994).

	Cd	Pb	Hg	Ni	Zn	Cu	Cr
1980	4.0	118	4.0	42.0	687	474	233
1991	1.7	36	2.1	12.4	376	399	30
1993	1.2	27	1.4	11.5	336	332	22

3. Data for Figure 3. Weighted average concentrations and total quantity of heavy metals in sludge annually produced in Norway (Data for 1993. Aquateam Norway 1994; Statistics Norway 1994).

	Cd	Pb	Hg	Ni	Zn	Cu	Cr
Concentration (mg/kg DS)	1.4	35	1.5	16	356	247	--
Total metal produced (kg)	106	2559	111	1181	26275	17350	--

4. Data for Figure 4. Annual loading rates of heavy metals from sludge application in Norwegian farmlands (Aquateam Norway 1994; Statistics Norway 1994).

		Cd	Pb	Hg	Ni	Zn	Cu	Cr
MPCso	(mg/kg DS)	1	50	1	30	150	50	100
MPCsl	(mg/kg DS)	4	100	5	80	1500	1000	125
BACsl	(mg/kg DS)	1.4	35	1.5	16	356	247	31
MPq	(g/ha)	8	200	10	160	3000	2000	250
AAq	(g/ha)	0.12	2.9	0.13	1.35	30.0	19.8	2.58

MPSso: maximum permissible concentrations of heavy metals in the soil.
MPCsl: maximum permissible concentrations of heavy metals in the sludge.
BACsl: average concentrations of heavy metals in the sludge produced in 1993.
MPq : maximum permissible loading of heavy metals from the sludge to the soil.
AAq : average loading of heavy metals from the sludge to cultivated lands excluding vegetable fields.

5. Data for Figure 5. Annual quantity (kg) of heavy metals generated from sludge in different counties of Norway (Aquateam Norway 1994; Statistics Norway 1994).

	Cd	Pb	Hg	Ni	Zn	Cu	Cr
Østfold	10.3	279	8.4	152	3098	1247	164
Akershus-Oslo	54.7	1182	49	553	10884	9677	1124
Hedmark	9.8	171	9	85	1568	1168	123
Oppland	7.7	151	11.7	55	1757	1422	199
Buskerud	7.1	318	10.7	86	3577	1923	216
Vestfold	3	155	4.1	51	1909	506	54
Telemark	5.9	201	8.8	110	1413	1221	268
Aust-Agder	1	20	0.8	13	367	266	64
Vest-Agder	7.5	117	8.8	106	2420	418	84
Others	14.0	351	15.2	164	3623	2337	351

6. Data for Figure 6. Annual average loading rates of heavy metals generated from sludge onto cultivated lands excluding fields for growing vegetables in Norway (Aquateam Norway 1994; Statistics Norway 1993; 1994) (g/ha/yr).

	Cd	Pb	Hg	Ni	Zn	Cu	Cr
Total	0.12	2.96	0.13	1.36	30.4	20.0	2.62
Østfold	0.13	3.65	0.11	1.99	40.5	16.3	2.15
Akershus-Oslo	0.67	14.6	0.6	6.82	134	119	13.9
Hedmark	0.09	1.65	0.09	0.82	15.1	11.3	1.19
Oppland	0.09	1.72	0.13	0.63	20.0	16.21	2.27
Buskerud	0.15	6.69	0.23	1.81	75.3	40.5	4.54
Vestfold	0.07	3.66	0.1	1.2	45.0	11.9	1.27
Telemark	0.25	8.66	0.38	4.74	60.9	52.6	11.6
Aust-Agder	0.09	1.9	0.08	1.27	34.9	25.3	6.08
Vest-Agder	0.49	7.86	0.58	6.96	158.8	27.48	5.51
Others	0.036	0.9	0.039	0.42	9.3	6.0	0.9

7. Data for Figure 7. Comparison of heavy metal concentrations (weighted average) in sludge produced in different countries (mg/kg DS) (Personal communications 1994).

Country (Year)	Cd	Pb	Hg	Ni	Zn	Cu	Cr
Norway (1993)	1.4	35	1.5	16	356	247	31
Sweden (1992)	1.7	50	1.9	18	584	391	38
Denmark (1992)	1.5	75	1.5	22	680	240	31
Finland (1992)	1.8	91	1.9	37	685	318	105
Germany (1991)	2.5	113	2.3	34	1045	322	62

8. Data for Figures 8. Phosphate fertilizer application in different counties of Norway during the period between July 1993 and June 1994 (Norsk Hydro 1994).

	Phosphorus (Ton)	Phosphorus (kg/ha/yr)
Total	13.688	16
Østfold	1.624	21
Akershus-Oslo	1.523	18
Hedmark	2.068	19
Oppland	1.158	12
Buskerud	0.816	16
Vestfold	0.960	22
Telemark	0.353	14
Aust-Agder	0.142	12
Vest-Agder	0.192	10
Others	4.852	9

9. Data for Figure 9. Soil cadmium input due to phosphorus application in Norway (Norsk Hydro 1994).

Year	Total Cd (Kg)	Cd per unit area (g/ha/yr)
1981	300	0.29
1982	100	0.1
1983	600	0.7
1984	1300	1.4
1985	1200	1.3
1986	1900	2.1
1987	800	0.9
1988	630	0.7
1989	300	0.3
1990	111	0.1
1991	43	0.05
1992	79	0.08
1993	94	0.09

10. Data for Figure 10. Heavy metals generated from phosphorus fertilizers applied in the period between July 1993 and June 1994 in different counties of Norway (kg) (Norsk Hydro 1994).

	Cd	Pb	Hg	Ni	Zn	Cu	Cr
Total	93.80	410.6	1.37	410.6	1369	2327	821.3
Østfold	11.12	48.7	0.16	48.7	162	276	97.4
Akershus-Oslo	10.13	45.7	0.15	45.7	152	259	91.4
Hedmark	14.17	62.0	0.21	62.0	207	352	124.1
Oppland	7.93	34.7	0.12	34.7	116	197	69.5
Buskerud	5.59	24.5	0.08	24.5	82	139	49.0
Vestfold	6.58	28.8	0.10	28.8	96	163	57.6
Telemark	2.42	10.6	0.04	10.6	35	60	21.2
Vust-Agder	0.97	4.3	0.01	4.3	14	24	8.5
Vest-Agder	1.32	5.8	0.02	5.8	19	33	11.5
Others	33.24	145.6	0.49	145.6	485	825	291.1

11. Data for Figure 11. Average loading rates of heavy metals due to application of phosphorus fertilizers onto Norwegian cultivated soils in the period between July 1993 and June 1994 (Norsk Hydro 1994; Statistics Norway 1993).

	Cd	Pb	Hg	Ni	Zn	Cu	Cr
Average	.113	.493	.0016	.493	1.64	2.79	.986
Østfold	.145	.633	.0021	.633	2.11	3.59	1.267
Akershus-Oslo	.128	.562	.0019	.562	1.87	3.18	1.124
Hedmark	.136	.595	.0020	.595	1.98	3.37	1.190
Oppland	.090	.394	.0013	.394	1.31	2.23	.789
Buskerud	.116	.508	.0017	.508	1.69	2.88	1.016
Vestfold	.150	.657	.0022	.657	2.19	3.72	1.314
Telemark	.104	.454	.0015	.454	1.51	2.57	.909
Aust-Agder	.090	.393	.0013	.393	1.31	2.23	.787
Vest-Agder	.085	.374	.0012	.374	1.25	2.12	.749
Others	.085	.372	.0012	.372	1.24	2.11	.745

12. Data for Figure 12. Soil Cd addition due to use of different types of phosphate fertilizers given that 25 kgs of P per hectare are annually applied (Norsk Hydro 1994).

Types	mg/kg P	Cd g/ha/yr
Major NPK fertilizer	0.65	0.016
NPK 6-7-21	45.75	1.14
NPK 25-3-6	80.35	2.0
PK 9-16	8.00	0.2
PK 7-18	50.00	1.25
PK 7-21	52.77	1.32
Pk 11-21	53.76	1.34
Superphosphate P9	55.57	1.39
Raw phosphate	40.00	1.02
Total	6.85	0.17
MPC*	100.00	2.5

**: MPC, the maximum Cd concentration in phosphate rocks permitted to be used for fertilizer production in Norway.*

13. Data for Figure 13. Concentrations of heavy metals in precipitation determined for different years at different observation stations of Norway (SFT Rapport 533:93 1993).

Year	Cd (μg/L)			Pb (μg/L)		
	Birkenes	Nordmoen	Osen	Birkenes	Nordmoen	Osen
1976	0.27			12.7		
1978	0.27			10.8		
1980	0.34			7.9		
1981	0.24			7.4		
1982	0.69			8.8		
1983	0.25			5.4		
1984	0.29			6.2		
1985	0.09			4.1		
1986	0.12			4.8		
1987	0.12	0.1		3.5	4.6	
1988	0.12	0.1	0.31	7.4	5.6	4.7
1989	0.11	0.08	0.08	5.4	4.6	2.7
1990	0.12	0.14	0.09	3.8	3.8	2.7
1991	0.06	0.06	0.03	3.6	2.6	2.0
1992	0.04	0.04	0.05	2.9	2.3	1.6

14. Data for Figure 14. Soil input of heavy metals from atmospheric deposition in different counties of Norway (Andersson A 1992; Kongshaug G 1992; SFT-rapport 93:533 1993) (g/ha/yr).

	Cd	Pb	Hg	Ni	Zn	Cu	Cr
Østfold	0.31	17.7	0.2	2.86	34.3	6.26	2.87
Akershus-Oslo	0.31	17.7	0.2	2.86	34.3	6.26	2.87
Hedmark	0.35	10.95	0.2	2.86	37.98	6.26	2.87
Oppland	0.35	10.95	0.2	2.86	37.98	6.26	2.87
Buskerud	0.35	10.95	0.2	2.86	37.98	6.26	2.87
Vestfold	0.31	17.7	0.2	2.86	34.3	6.26	2.87
Telemark	0.22	20.15	0.2	2.86	41.35	6.26	2.87
Aust-Agder	0.5	38.6	0.2	2.86	70.41	6.26	2.87
Vest-Agder	0.5	38.6	0.2	2.86	70.41	6.26	2.87
Others	0.21	3.67	0.2	3.0	12.7	3.83	2.87
Average	0.35	21.85	0.2	2.86	46.0	6.26	2.87

15. Data for Figure 15. Total quantity of heavy metals taken up by crops in different counties of Norway (Anderssion 1992; Statistics Norway 1993; Låg and Steinnes 1977; Wu and Aasen 1994; Wu and Selmer-Olsen 1992) (kg).

	Cd	Pb	Hg	Ni	Zn	Cu	Cr
Total	461.0	4388	70.2	2710	100897	21837	544.0
Østfold	15.1	94	1.7	160	7468	1364	15.6
Akershus-Oslo	14.1	97	1.8	157	7154	1293	15.3
Hedmark	32.9	259	4.5	265	11596	2270	36.1
Oppland	40.3	389	6.1	233	9067	1998	48.3
Buskerud	11.8	97	1.6	81	3534	705	13.4
Vestfold	7.5	39	0.8	67	3369	635	7.0
Telemark	6.0	54	0.9	40	1656	344	7.0
Aust-Agder	5.1	48	0.8	23	830	189	5.9
Vest-Agder	10.2	100	1.6	47	1539	359	11.9
Others	318.1	3212	50.3	1637	54705	12686	383.5

16. Data for Figure 16. Uptake of heavy metals by crops in different counties of Norway (Anderssion 1992; Statistics Norway 1993; Låg and Steinnes 1977; Wu and Aasen 1994; Wu and Selmer-Olsen 1992) (g/ha/yr).

	Cd	Pb	Hg	Ni	Zn	Cu	Cr
Average	0.52	4.97	0.080	3.07	114.25	24.73	0.62
Østfold	0.20	1.22	0.022	2.07	97.09	17.73	0.20
Akershu-Oslo	0.17	1.19	0.022	1.93	87.99	15.90	0.19
Hedmark	0.32	2.48	0.043	2.54	111.17	21.76	0.35
Oppland	0.46	4.42	0.069	2.65	102.91	22.68	0.55
Buskerud	0.24	2.01	0.034	1.68	73.31	14.62	0.28
Vestfold	0.17	.89	0.018	1.54	76.87	14.49	0.16
Telemark	0.26	2.32	0.038	1.72	71.03	14.73	0.30
Aust-Agder	0.47	4.42	0.074	2.14	76.60	17.48	0.55
Vest-Agder	0.66	6.51	0.106	3.08	100.01	23.33	0.78
Others	0.81	8.22	0.129	4.19	139.95	32.45	0.98

17. Data for Figure 17. Soil heavy metal input due to sludge application, fertilization and atmospheric deposition and output due to plant uptake and leaching (Andersson 1992; Norsk Hydro 1994; SFT-rapport 533:93 1993; Statistics Norway 1993; 1994). (Average for Norway g/ha/yr).

	Sludge	Fertilizer	Deposition	Uptake	Leaching	Input	Output
Cd	0.12	0.11	0.35	0.52	0.10	0.58	0.62
Pb	2.96	0.50	21.85	4.97	0.60	25.31	5.57
Hg	0.13	0.0016	0.20	0.080	0.01	0.332	0.09
Ni	1.36	0.49	2.86	3.070	4.00	4.71	7.07
Zn	30.40	1.60	46.00	114.25	8.00	78.00	122.25
Cu	20.00	2.80	6.26	24.73	4.00	29.06	28.37
Cr	2.62	0.99	2.87	0.62	0.80	6.42	1.42

18. Data for Figure 19. Soil heavy metal input due to sludge application, fertilization and atmospheric deposition and output due to plant uptake and leaching (Andersson 1992; Norsk Hydro 1994; SFT-rapport 533:93 1993; Statistics Norway 1993; 1994) (Østfold g/ha/yr).

	Sludge	Fertilizer	Deposition	Uptake	Leaching	Input	Output
Cd	0.13	0.145	0.31	0.20	0.10	0.59	0.30
Pb	3.65	0.633	17.70	1.22	0.60	22.00	1.82
Hg	0.11	0.0021	0.20	0.022	0.01	0.312	0.032
Ni	1.99	0.633	2.86	2.07	4.00	5.48	6.07
Zn	40.50	2.110	34.30	97.09	8.00	76.91	105.09
Cu	16.30	3.590	6.26	17.73	4.00	26.15	21.73
Cr	2.15	1.267	2.81	0.20	0.80	6.23	1.00

19. Data for Figure 21. Soil heavy metal input due to sludge application, fertilization and atmospheric deposition and output due to plant uptake and leaching (Andersson 1992; Norsk Hydro 1994; SFT-rapport 533:93 1993; Statistics Norway 1993; 1994) (Akershus-Oslo g/ha/yr).

	Sludge	Fertilizer	Deposition	Uptake	Leaching	Input	Output
Cd	0.67	0.128	0.31	0.17	0.10	1.11	0.27
Pb	14.60	0.562	17.70	1.19	0.60	32.86	1.79
Hg	0.60	0.0019	0.20	0.022	0.01	0.80	0.032
Ni	6.82	0.562	2.86	1.93	4.00	10.24	5.93
Zn	134.00	1.870	34.30	87.99	8.00	170.17	95.99
Cu	119.00	3.180	6.26	15.90	4.00	128.44	19.90
Cr	13.90	1.124	2.81	0.19	0.80	17.83	0.99

20. Data for Figure 23. Soil heavy metal input due to sludge application, fertilization and atmospheric deposition and output due to plant uptake and leaching (Andersson 1992; Norsk Hydro 1994; SFT-rapport 533:93 1993; Statistics Norway 1993; 1994) (Hedmark g/ha/yr).

	Sludge	Fertilizer	Deposition	Uptake	Leaching	Input	Output
Cd	0.09	0.136	0.35	0.32	0.10	0.58	0.42
Pb	1.65	0.595	10.95	2.48	0.60	13.20	3.08
Hg	0.09	0.002	0.20	0.043	0.01	0.292	0.053
Ni	0.82	0.595	2.86	2.54	4.00	4.28	6.54
Zn	15.10	1.980	37.98	111.17	8.00	55.06	119.17
Cu	11.30	3.370	6.26	21.76	4.00	20.93	25.76
Cr	1.19	1.190	2.81	0.35	0.80	5.19	1.15

21. Data for Figure 25. Soil heavy metal input due to sludge application, fertilization and atmospheric deposition and output due to plant uptake and leaching (Andersson 1992; Norsk Hydro 1994; SFT-rapport 533:93 1993; Statistics Norway 1993; 1994) (Oppland g/ha/yr).

	Sludge	Fertilizer	Deposition	Uptake	Leaching	Input	Output
Cd	0.09	0.090	0.35	0.46	0.10	0.53	0.56
Pb	1.72	0.394	10.95	4.42	0.60	13.06	5.02
Hg	0.13	0.0013	0.20	0.069	0.01	0.331	0.079
Ni	0.63	0.394	2.86	2.65	4.00	3.88	6.65
Zn	20.00	1.310	37.98	102.91	8.00	59.29	110.91
Cu	16.20	2.230	6.26	22.68	4.00	24.69	26.68
Cr	2.27	0.789	2.81	0.55	0.80	5.87	1.35

22. Data for Figure 27. Soil heavy metal input due to sludge application, fertilization and atmospheric deposition and output due to plant uptake and leaching (Andersson 1992; Norsk Hydro 1994; SFT-rapport 533:93 1993; Statistics Norway 1993; 1994) (Buskerud g/ha/yr).

	Sludge	Fertilizer	Deposition	Uptake	Leaching	Input	Output
Cd	0.10	0.116	0.35	0.24	0.10	0.57	0.34
Pb	6.69	0.508	10.95	2.01	0.60	18.15	2.61
Hg	0.23	0.0017	0.20	0.034	0.01	0.432	0.044
Ni	1.81	0.508	2.86	1.68	4.00	5.18	5.68
Zn	75.30	1.690	37.98	73.31	8.00	114.97	81.31
Cu	40.50	2.880	6.26	14.62	4.00	49.64	18.62
Cr	4.54	1.016	2.81	0.28	0.80	8.37	1.08

23. Data for Figure 29. Soil heavy metal input due to sludge application, fertilization and atmospheric deposition and output due to plant uptake and leaching (Andersson 1992; Norsk Hydro 1994; SFT-rapport 533:93 1993; Statistics Norway 1993; 1994) (Vestfold g/ha/yr).

	Sludge	Fertilizer	Deposition	Uptake	Leaching	Input	Output
Cd	0.07	0.150	0.31	0.17	0.10	0.53	0.27
Pb	3.66	0.657	17.70	0.89	0.60	22.07	1.49
Hg	0.10	0.0022	0.20	0.018	0.01	0.302	0.028
Ni	1.20	0.657	2.86	1.54	4.00	4.72	5.54
Zn	45.00	2.190	34.30	76.87	8.00	81.49	84.87
Cu	11.90	3.720	6.26	14.49	4.00	21.88	18.49
Cr	1.27	1.314	2.81	0.16	0.80	5.39	0.96

24. Data for Figure 31. Soil heavy metal input due to sludge application, fertilization and atmospheric deposition and output due to plant uptake and leaching (Andersson 1992; Norsk Hydro 1994; SFT-rapport 533:93 1993; Statistics Norway 1993; 1994) (Telemark g/ha/yr).

	Sludge	Fertilizer	Deposition	Uptake	Leaching	Input	Output
Cd	0.25	0.104	0.22	0.26	0.10	0.57	0.36
Pb	8.66	0.454	20.15	2.32	0.60	29.26	2.92
Hg	0.38	0.0015	0.20	0.038	0.01	0.58	0.48
Ni	4.74	0.454	2.86	1.72	4.00	8.05	5.72
Zn	60.90	1.510	41.35	71.03	8.00	103.76	79.03
Cu	52.60	2.570	6.26	14.73	4.00	61.43	18.73
Cr	11.60	0.909	2.81	0.30	0.80	15.32	1.10

25. Data for Figure 33. Soil heavy metal input due to sludge application, fertilization and atmospheric deposition and output due to plant uptake and leaching (Andersson 1992; Norsk Hydro 1994; SFT-rapport 533:93 1993; Statistics Norway 1993; 1994) (Aust-Agder g/ha/yr).

	Sludge	Fertilizer	Deposition	Uptake	Leaching	Input	Output
Cd	0.09	0.090	0.50	0.47	0.10	0.68	0.57
Pb	1.90	0.393	38.60	4.42	0.60	40.89	5.02
Hg	0.08	0.0013	0.20	0.074	0.01	0.28	0.08
Ni	1.27	0.393	2.86	2.14	4.00	4.52	6.14
Zn	34.90	1.310	70.41	76.60	8.00	106.62	84.60
Cu	25.30	2.230	6.26	17.48	4.00	33.79	21.48
Cr	6.08	0.787	2.81	0.55	0.80	9.68	1.35