Heavy-metal balances of agro-ecosystems in the Netherlands

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Abstract

In this paper, heavy-metal flows (cadmium, copper, lead, and zinc) of arable, dairy and mixed farming systems in the Netherlands are studied. Farm-gate and field-scale balances are calculated. On the field-scale, static and dynamic balances are distinguished. By determining the characteristic metal flows, it becomes possible to differentiate between farming systems and to select the most viable options for sustainable heavy-metal management. The crop rotation and the choice of fertilizers clearly influence the heavy-metal balance of arable farming systems. In dairy farming systems, the role of feed management is very important, but the effects on the heavy-metal balance are not always straightforward. Mixed farming systems compare favorably with specialized (arable or dairy) farming systems with regard to heavy-metal accumulation. Due to the internal cycling of feedstuff and manure, less inputs are required and thus the inport of heavy-metal containing raw materials and products is minimized. Uncertainties related to the calculation of heavy-metal balances are discussed.

Keywords: heavy metals, heavy-metal balance, agro-ecosystem, arable farming, dairy farming, mixed farming.

Introduction

Accumulation of heavy metals in agricultural soil may cause problems if certain levels are exceeded. If soil is to permanently fulfil its functions in agricultural production, in environmental processes, and as a habitat of numerous organisms, heavy-metal accumulation has to be restricted. To this end, heavy-metal flows in agro-ecosystems have to be analyzed to identify the most important sources and processes that lead to accumulation. Based on such an analysis, preventive measures may be defined.

The balance approach has proven to be useful in soil fertility studies to demonstrate depletion of nutrients from soils (e.g. Frissel, 1978; Smaling, 1993). This approach can also be used in soil pollution research to demonstrate accumulation of heavy metals in agricultural soils (Van Driel & Smilde, 1990). Heavy-metal balances thus serve to identify both management options and emissions from the soil to other environmental compartments.

In this paper, we analyse cadmium (Cd), copper (Cu), lead (Pb), and zinc (Zn) flows and their balances at field and farm level for arable, dairy and mixed farming systems in the Netherlands. Quantifying the characteristic flows from literature data and measurements at experimental farms allows comparison of different systems and identification of the most viable options for sustainable heavy-metal management.

Modelling heavy-metal flows on different spatial scales

The spatial scale of analysis influences the calculation of heavy-metal balances. Analyses at national level cannot pay attention to relevant processes on smaller scales, because site-specific aspects are averaged out. It is therefore necessary to study heavy-metal balances on farm and field scale as well to get insight in the extent of accumulation in different agro-ecosystems (Moolenaar, 1997).

Farm-gate balance

If the agro-ecosystem's borders are drawn at the farm-gate, an analysis at farm level can be carried out. The input and output flows vary strongly among farming systems and the farm-gate balance shows the characteristic flows and processes of a farm as a whole. The farm-gate balance is useful, since management measures take place at farm level.

Field-scale balance

An analysis on farm scale does not distinguish among the soil, animal and plant compartments. The input and output flows between these compartments (i.e., internal flows) vary largely among farming systems. The field-scale balance shows the balance sheets for the soil compartment or the plough layer of individual fields. In arable farming systems, the balance on farm and field scale is almost identical. If internal flows play an important role, as in dairy and mixed farming systems, the farm-gate balance differs from the field-scale balance.

A balance equation for the plough layer relates the rates of change in heavy-metal content, input and output and is given by:

$$\Delta G^* = I - O \qquad (1)$$

The change in total heavy-metal content in the plough layer (ΔG^*) is the balance of the input (I) at the soil surface and the output (O) by leaching out of the plough layer and by removal in harvested products. Losses to the atmosphere in the case of volatile metals and losses by (wind and water) erosion may be incorporated in the balance equation if appropriate. In a 'static' balance, a record is kept of the input and output flows for one year or one crop rotation (g m^{-2} yr^{-1}). For a simulation of the long-term behavior in time, a 'dynamic' balance may be defined in which the relationships between soil content (G; g m^{-3}) and outputs in time are explicitly included:

$$\frac{dG}{dt} = A - L - U \tag{2}$$

Here, A is the input rate, L is the leaching rate and U is the uptake and removal rate by crops (g m^{-3} yr^{-1}). The leaching rate (L) is the product of precipitation surplus and heavy-metal concentration in solution (c: g m^{-3}) and hence:

$$L = \frac{P_s c}{l_p} \tag{3}$$

Here, P_s equals the precipitation surplus in the 'average' Dutch situation (i.e., 0.3 m yr^{-1}). The plough layer depth (l_p) is ca. 0.3 m in most arable farming systems. By measuring adsorption isotherms, the relationship between the concentration in solution (c) and the adsorbed amount of heavy metals (q: g kg^{-1}) can be derived assuming that equilibrium is instantaneous and that no desorption hysteresis occurs. Adsorption can for instance be modelled with the Freundlich sorption equation, given by:

$$q = k_f c^n \tag{4}$$

where k_f and n are soil-dependent constants.

The plant uptake rate (U) is expressed here according to the relationship:

$$U = k_{up} G^m \tag{5}$$

(cf. Kuboi *et al.*, 1986). The value of m depends on the uptake behaviour and may be larger than 1 (accumulators), smaller than 1 (excluders) or equal to 1 (indicators). The plant uptake rate coefficient, k_{up} (yr^{-1}), is related to crop yield (Y: kg m^{-2} yr^{-1}), metal content in the crop (c_p: g kg^{-1}), and soil content (G) according to:

$$k_{up} = \frac{Y c_p}{l_p G} \tag{6}$$

Arable farming system

Arable farming systems are characterized by their crop rotation. In such systems, the most important inputs are mineral (N, P, K, Ca) fertilizers, animal manure, organic amendments (sewage sludge and compost), and atmospheric deposition. The output consists of produce (crops) and leaching out of the plough layer. Since the internal cycle is represented by transfer of crop residues only, it is quite small (Figure 1).

Three arable farming systems as practised at Nagele experimental farm (in the Northeast polder; 52°39′ N, 5°44′ E) were chosen for this study i.e., conventional

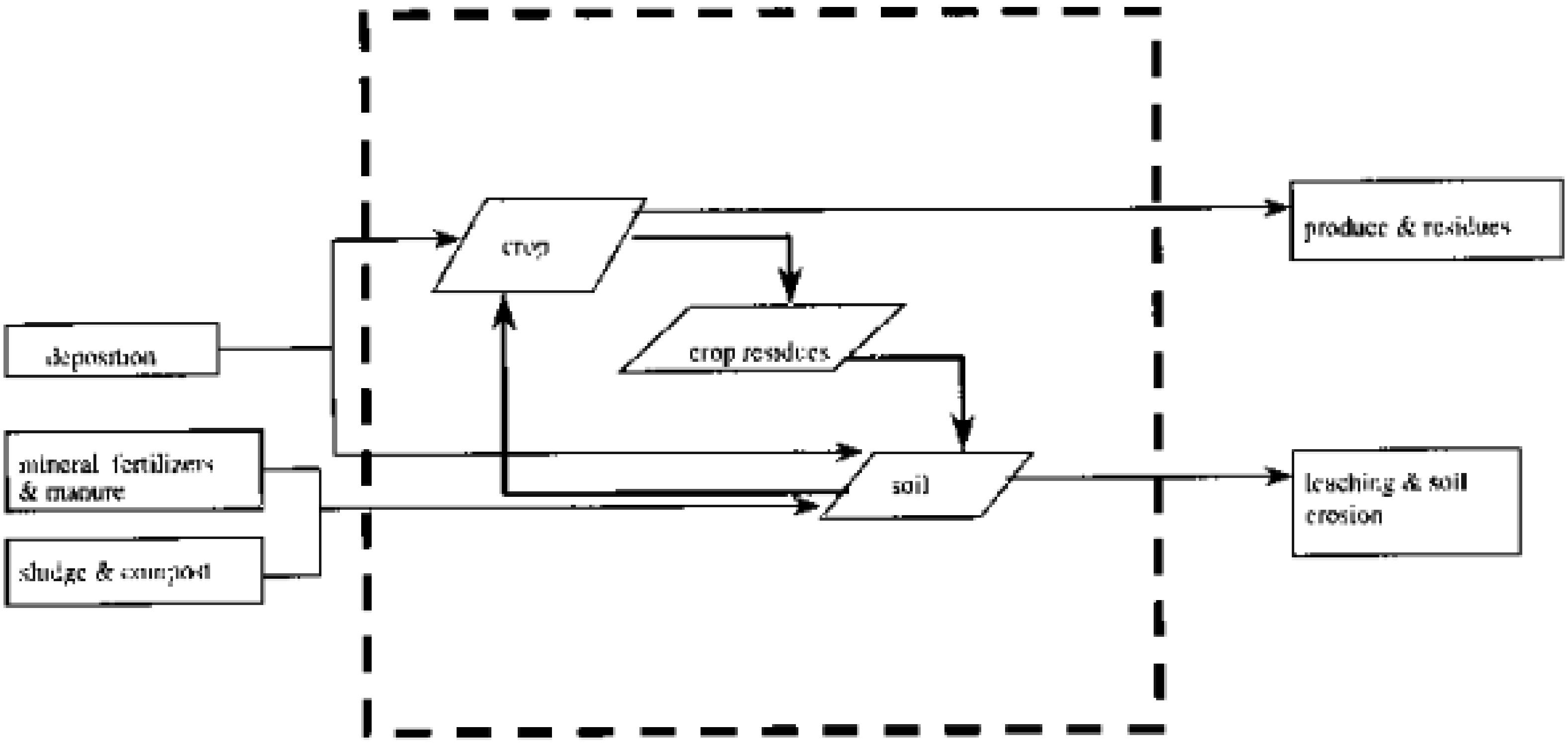

Figure 1. Arable farming system; input, internal (heavy solid arrows), and output flows.

(CAFS: 22.7 ha), integrated (IAFS: 17 ha), and ecological (EAFS: 22.2 ha). The 4-year crop rotation of the conventional system consists of ware and seed potato, sugar beet, chicory and onion, winter wheat and spring barley. This system comprises two parts, one with mineral fertilizers only (CAFS-MF: 14 ha) and one with both mineral and organic fertilizers (CAFS-OF: 8.7 ha). The crop rotation in the integrated system is similar to that in the conventional system (carrot instead of chicory). The 6-year crop rotation of the ecological system consists of seed potato, spring wheat, celery and onion, spring barley, carrot, and oats (Vereijken, 1992).

Heavy-metal balance sheets for the three systems were calculated. Soil samples were taken from the plough layer (top 30 cm) of each individual field (30 samples in total) and analysed for Cd, Cu, Pb, and Zn. General soil characteristics and average heavy-metal contents are given in Table 1. Detailed information on soil, fertilizer, and plant analyses is given in Hatziotis (1995) for Cd and Zn and in Van Kuik (1995) for Cu and Pb.

Table 1. General characteristics and heavy-metal contents of the Nagele soil.

pH-KCl:	7.4
Organic matter content (mass %):	2.6
Clay content (mass %):	24
$CaCO_3$ content (mass %):	10
ρ (kg m^{-3})	1400
P_w -number:	25
K-number:	17
Cd content (mg kg^{-1}):	0.5 (0.48-0.52)
Cu content (mg kg^{-1}):	23 (19-27)
Pb content (mg kg^{-1}):	35 (33-38)
Zn content (mg kg^{-1}):	100 (99-107)

Inputs

At Nagele, the most important sources are atmospheric deposition and fertilizer application. Irrigation water samples from a nearby ditch did not show detectable levels of heavy metals. Inputs via atmospheric deposition were based on measurements at Biddinghuizen near Nagele (Aben *et al.*, 1992). During the growing season 1993-1994, various fertilizers were used: in CAFS-MF mineral fertilizer only, in EAFS organic fertilizers (solid goat and cattle manure) only, and in IAFS and CAFS-OF a combination of organic and mineral fertilizers. Phosphate requirements were met with liquid poultry manure in IAFS and CAFS-OF and with triple superphosphate (TSP) in CAFS-MF. Nitrogen and potassium requirements were met with ammonium nitrate limestone (CAN) and muriate of potash (K-60), respectively. Fertilizer applications and heavy-metal contents in these fertilizers are shown in Table 2 and Table 3, respectively.

Crop removal

Total metal removal in crops is calculated from yield (defined as dry weight at economic maturity stage) removed from the fields and crop metal contents. Green materials recycled within the farm (as grass, clover, lucerne, leaves of sugar beet, and leaves of celeriac) are not included in the calculation of total output. Straw was taken

Table 2. Manure and fertilizer inputs (kg dry weight) in the growing season 1993/1994 and surface area (ha) for the farming systems at Nagele experimental farm.

	Ecological	Integrated	Conventional	
			organic fert.	mineral fert.
Surface area	22.2	17	8.7	14
Poultry manure	0	19695	11263	0
Goat manure	45859	0	0	0
Cattle manure	16352	0	0	0
Ammonium nitrate limestone	0	4250	1782	5367
Muriate of potash (K-60)	0	4887	2322	5211
Triple super phosphate (TSP)	0	0	0	2025

Table 3. Heavy-metal contents in manure and fertilizers (mg kg^{-1} dry weight) used at Nagele experimental farm (CAN: ammonium nitrate limestone).

	Cd	Cd (mg kg^{-1} P_2O_5)	Cu	Pb	Zn
Poultry manure	0.42	7.7	72.7	4.9	647
Goat manure	0.38	30.6	45.9	11.9	157
Cattle manure	0.37	20.7	33.2	31.9	167
CAN	0		0.45	0.4	1.78
K-60	0	-	0.48	1.1	1.38
TSP	31.4	68.4	43.9	3.9	593

Table 4. Area-weighted mean heavy-metal offtake by crops (g ha^{-1} yr^{-1}) in four arable farming systems (and average numbers for the conventional systems) at Nagele experimental farm.

	Cd	Cu	Pb	Zn
Ecological	0.6	33.3	1.24	138
Integrated	0.94	48.7	1.58	204
Conventional (organic fert.)	0.78	58.3	2.62	190
Conventional (mineral fert.)	0.82	50.5	2.2	187
Conventional (average)	0.81	53.5	2.35	188

off the field and sold. The area-weighted mean values for crop removal of the 4 farming systems are shown in Table 4. Output in produce is lowest in EAFS since crop yields are lowest and part of the area is taken up by hedgerows as so-called ecological infrastructure.

Leaching

Metal solubility is expected to be low in this calcareous soil. As Cd, Cu, Pb and Zn co-exist in the soil solution, we have determined competitive adsorption isotherms for the mixture of Cd, Cu, Pb and Zn at soil pH in order to determine the solute concentrations. The concentration ranges in the mixture correspond to those resulting from deposition and fertilizers. The competitive cations Ca, Na, and K were added in the ratio 3:1:1.

Lead was not present in detectable concentrations (< 16 µg l^{-1}) in the equilibrium solution. Hence, no adsorption isotherm could be constructed. For Cd, Cu and Zn, a Freundlich type relationship between concentration in solution (c) and adsorbed amount (q) could be fitted (Table 5). The initial solution concentrations calculated by substituting the q_i values (Table 5) in the adsorption models for Cd, Cu and Zn equal 0.02, 2.7, and 0.2 (mg m^{-3}), respectively. Multiplying these concentrations with the precipitation surplus, results in leaching of 0.06, 8.1, and 0.6 (g ha^{-1} yr^{-1}) for Cd, Cu and Zn, respectively.

Balances

The static balances of Cd, Cu, Pb and Zn in the farming systems are presented in Figures 2a–2d, respectively.

Table 5. Adsorption models for Cd, Cu, and Zn in the Nagele soil expressing the relationship between concentration in solution (c: mg m^{-3}) and the adsorbed amount (q: mg kg^{-1}). The initially adsorbed amount is given by the value of q_i.

	adsorption model	r^2	q_i
Cd:	$c = 0.19q^{1.47}$	0.99	0.24
Cu:	$c = 0.026q^{1.46}$	0.89	23.8
Zn:	$c = 3.54\ 10^{-5}q^{2.79}$	0.99	51.7

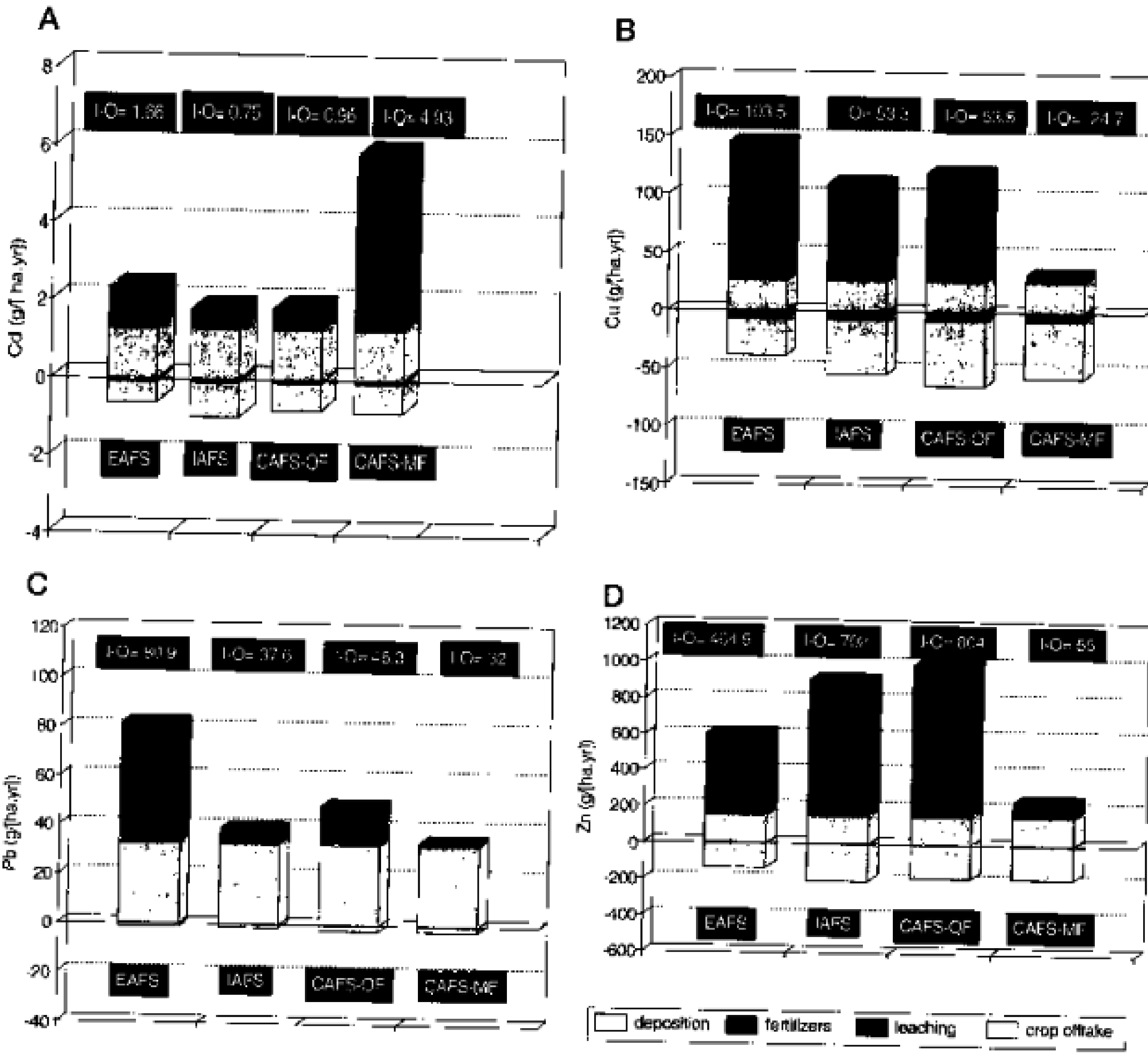

Figure 2. Annual Cd (2a), Cu (2b), Pb (2c), and Zn (2d) input (I) and output (O) flows for ecological (EAFS), integrated (IAFS), and conventional (mineral fertilizers only: MF, mineral and organic fertilizers: OF) arable farming systems at Nagele experimental farm.

As an illustration of long-term simulation, the dynamic balance approach was applied to Cd and Cu, which represent extreme cases in the conventional arable farming system (CAFS-average). Soil bulk density and plough layer thickness may not be constant in time due to changes in organic matter content and input or output of soil particles by processes like erosion. This is recognized by the so-called dynamic soil composition balance approach (DSCB), which takes into account changes in soil composition while calculating the dynamic balance (Moolenaar *et al.*, 1997a). Because these changes in soil composition are not known, they are not regarded in this analysis.

The values for the parameters A (Tables 2, 3 and Figures 2a, 2b), U (with area-weighted mean values of the individual k_{up}-values given in Table 6) and L (with solute concentration based on the adsorption models in Table 5) were substituted in

Table 6. Cd and Cu uptake rate constants (k_{up}: 10^{-4} yr^{-1}) for different arable farming systems at Nagele experimental farm (area-weighted mean values).

	Ecological	Integrated	Conventional		
			organic fert.	mineral fert.	total
Cd	5.92	10.43	9.07	7.99	8.4
Cu	3.39	5.31	5.78	5.19	5.42

the balance equation. The development of soil content, leaching and uptake in the conventional system (total) is shown in Figures 3 (Cd) and 4 (Cu). Soil Cd content will exceed the Dutch reference value (defined as [0.4 – 0.007{C + 3H}] with mass % clay (C) and mass % organic matter (H), i.e., 0.6 mg kg^{-1} for this soil) and develop towards a steady state value of ca. 1.7 mg kg^{-1} (Figure 3). The high (average) offtake rate will result in quality standards of some crops being exceeded as shown by Moolenaar *et al.* (1997b). For Cu, the total soil content decreases to 14 mg kg^{-1} at steady state, with the associated reduction in leaching and crop offtake (Figure 4). These dynamic balance calculations illustrate that it is possible to compare and judge the long-term behavior of different heavy metals. Atmospheric deposition, crop rotation and selection of fertilizers directly influence both the annual balance

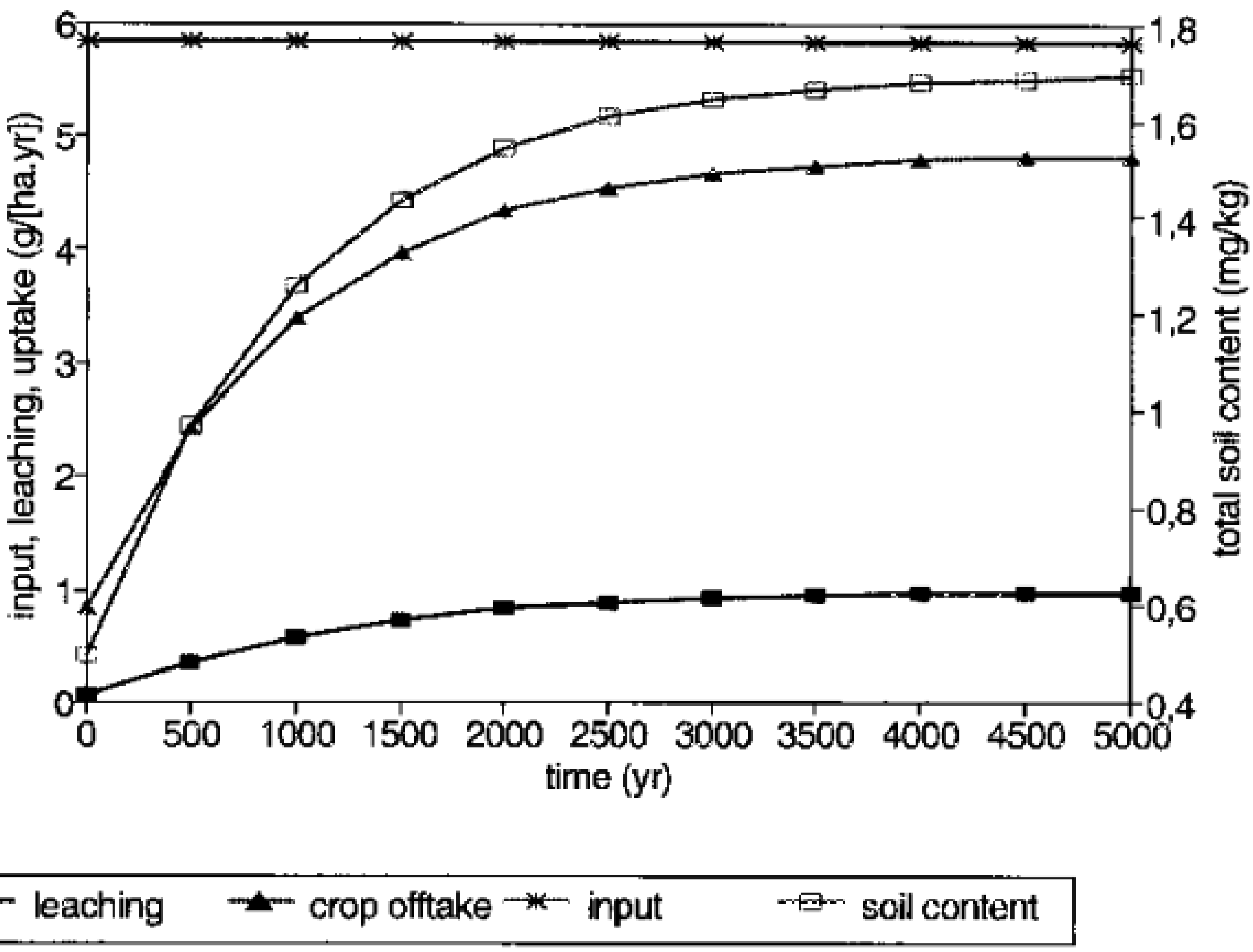

Figure 3. Development of Cd input and soil content, leaching and uptake rates in the conventional arable farming system.

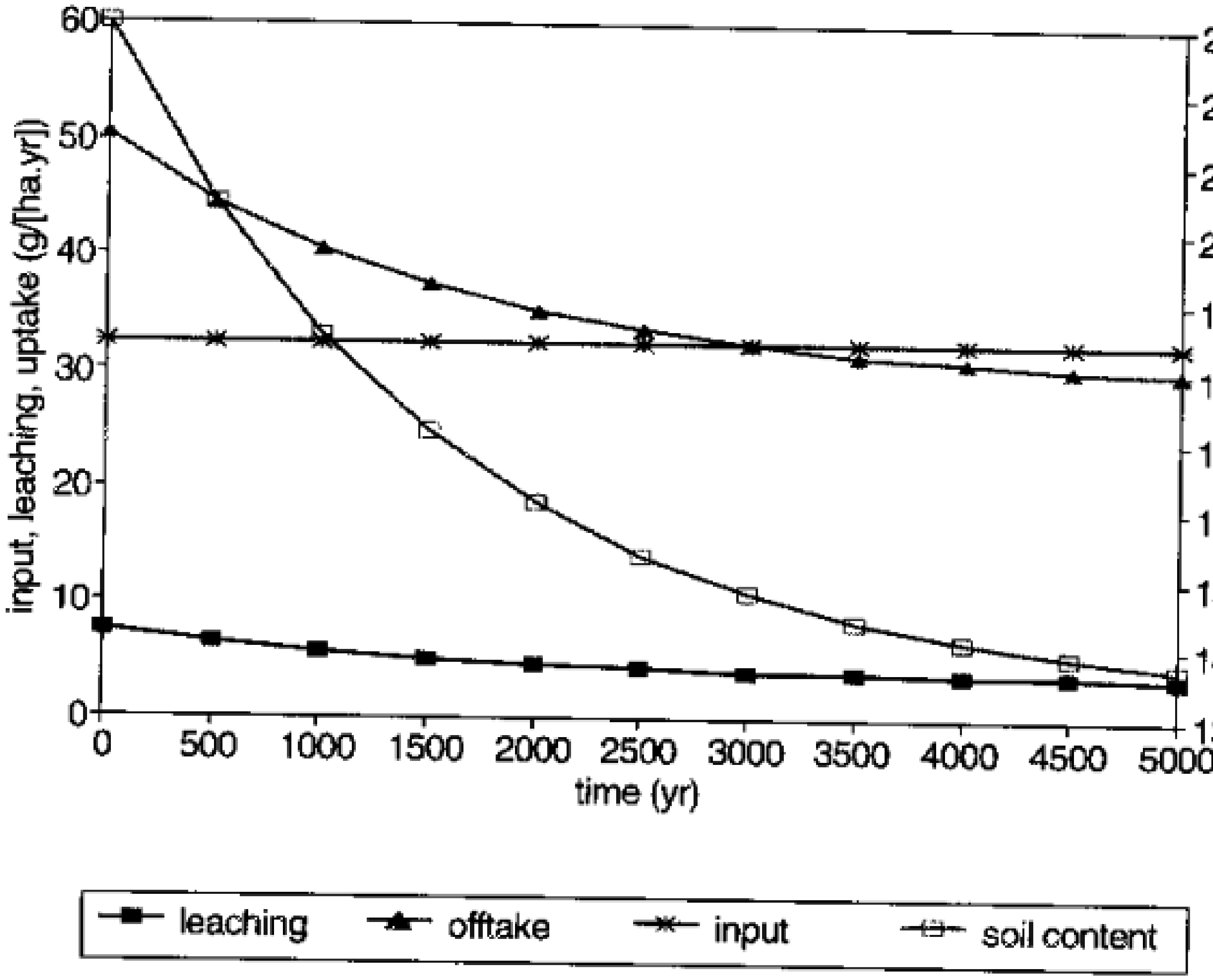

Figure 4. Development of Cu input and soil content, leaching and uptake rates in the conventional arable farming system.

and the long-term development of heavy-metal concentrations in soil, groundwater and crops.

Dairy farming system

Dairy farming is the most important sector of Dutch agriculture. It occupies ca. 65% of the cultivated area and provides the main income to 35% of the Dutch farmers. A dairy farm is characterized by the combination of plant and animal production (Figure 5). The most important compartments in dairy farming are soil, roughage (grass and possibly maize), manure and livestock. In general, heavy-metal flows in dairy farming systems are smaller than in arable farming systems. However, due to the internal cycles, the balance may be more difficult to influence by farm management.

Manure is not always imported since on-farm manure production may be (more than) sufficient. In Figure 5, possible inputs through biocides, detergents for disinfection and cleaning, drinking, irrigation and cleaning water, artificial milk, seeds and others are neglected. For example, the heavy-metal balance is influenced by the

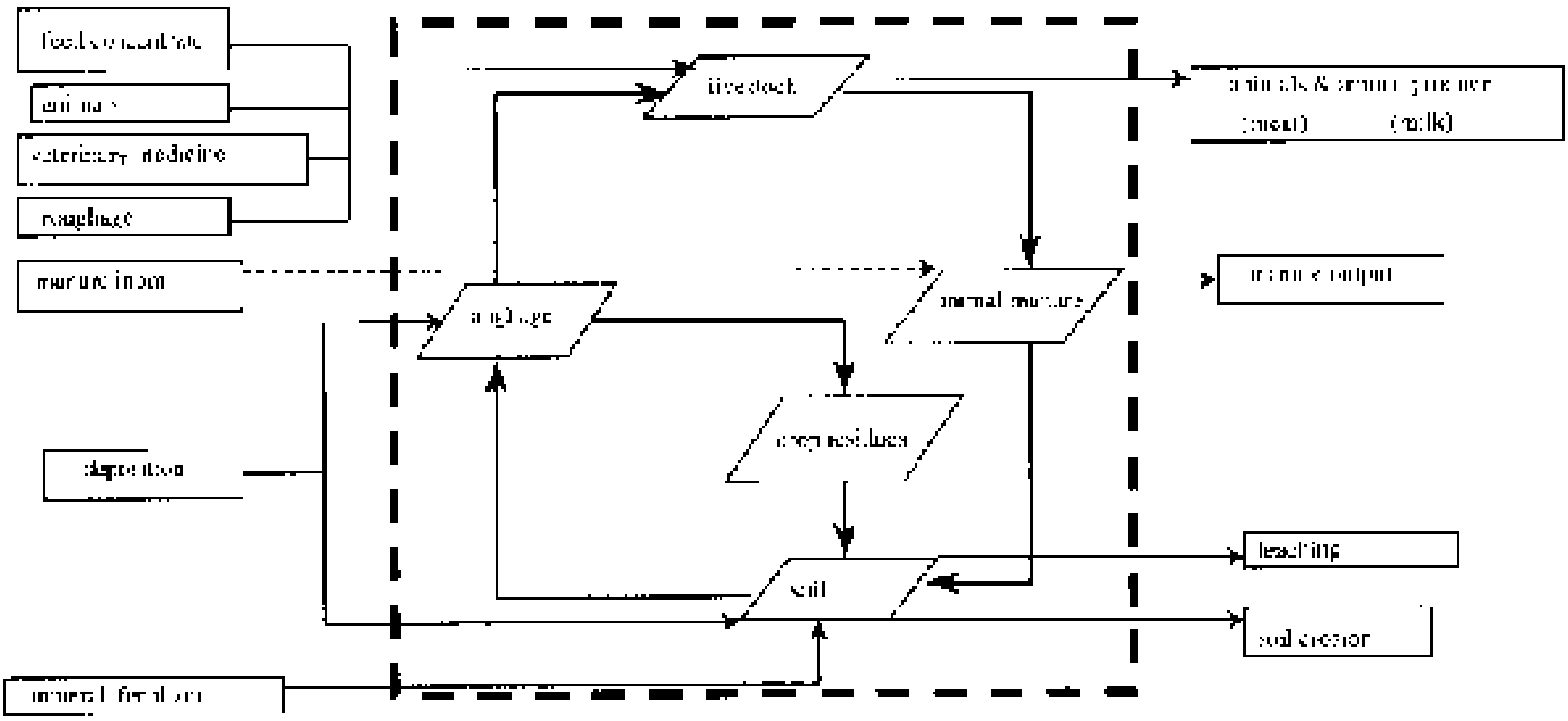

Figure 5. Dairy farming system: input, internal (heavy solid arrows), and output flows.

number of animals and forage production, which influence the amount of inputs required. In the past, milk production systems were characterized by careful use of animal manure as part of the integration of arable and dairy farming. These systems have been strongly intensified through increased inputs of mineral N-fertilizers and purchased feeds which has led to a serious imbalance between inputs of nutrients and outputs in milk and meat. On Dutch dairy farms, average annual milk production is about 11500 kg ha^{-1} and output represents on average 14% of the input for N, 32% for P, and 17% for K (Aarts *et al.*, 1992). Fertilizer application rates vary widely within the same type of farming system. Poppe *et al.* (1994) found a mean application rate of 250 kg N ha^{-1} with a range of ca. 100–360. Higher N-fertilizer applications result in slightly higher heavy-metal inputs. However, they may also lead to increased forage production and consequently lower inputs of purchased feed (roughage and concentrates) and associated heavy-metals.

Van Hooft (1995) established the risks for public health due to uptake of heavy metals by cows during grazing. The transfer coefficients from soil to animals depend on element, concentration in feed, amount of feed, and by absorption, internal distribution, and retention of the elements in the animal's body. Cadmium and Pb end up mainly in liver and kidney and Cu in the liver. There are indications that Cd and Pb concentrations in liver and kidney are directly related to the contents in feed. Muscular tissue and milk are hardly contaminated with heavy metals. Animal intake of grass (including adhering soil), other roughages, and feed concentrates were identified as the most significant sources of heavy-metals in cows. Inhalation, dermal uptake, and water consumption were not considered to be significant pathways of exposure. Most heavy metals ingested are excreted and only ca. 5% is retained in the body (Van Hooft, 1995).

Vreman & Vos (1987) carried out an extensive survey of heavy-metal contents in raw materials used for feed production of plant, animal and mineral origin. They concluded that contents in raw materials and in concentrates also depend on additions and contamination during production, transport and storage of the feed. They showed that although Cd contents in raw materials generally were below the detection limit, in the concentrates they were higher due to contamination during processing.

Metal contents in animal manure can be estimated in various ways. Total intake with feed can be calculated by measurement of feed consumption and contents. The contents in manure may then be derived from the fraction retained in the animal. Alternatively, manure samples may be analyzed directly. The first approach was followed by Van Der Veen *et al.* (1993) by calculating mineral balance sheets for monitored farms. They assumed that animal manure and mineral fertilizer applications determine crop yield, which in turn determines roughage availability. Feed requirements were based on milk production per animal, and the feed balances yield the buying and selling of roughage and the manure production. Anonymous (1997) used both approaches in a complementary way to calculate heavy-metal balances for dairy farming systems with varying soil type (sand, clay, peat), livestock density (1.5, 2.25, 3 dairy cows per hectare), and growing of silage maize (clay and peat: 0% of farm area; sand: 20 or 30% of farm area). The inputs consisted of roughage, concentrates and mineral fertilizers. The outputs consisted of meat, milk, roughage, and animal manure. All systems show a Cd surplus which is largely determined by fertilizer use. Fattening pig manure systems show the highest Cu surplus, since Cu is added to feed concentrates (albeit in lower contents than in the past). Fattening pig manure also causes the highest Zn surplus in the fertilization scenarios, followed by systems with high livestock densities. The latter have high Zn inputs due to imported silage maize (roughage) and formula feed (concentrate). These findings were confirmed by Blaauw & Kuypers (1994), who found that for the field-scale balance of a hypothetical specialized dairy farming system, the most important inputs were mineral fertilizers (Cd, Pb), concentrates (Cd, Cu, Zn), deposition (Pb, Cu, Zn), and roughage (Zn).

Mixed farming system

The mixed farming system (Figure 6) is very similar to the dairy farming system except that there may be output of roughage (grass and maize) and arable crops.

External inputs as mineral fertilizers, concentrates and biocides were not used in large quantities until the second half of this century, as production was based on locally available resources from recycling of minerals in manure and other 'waste'. Since the 50's, technological innovations, cheap raw materials, higher wages, and favorable terms of trade for agricultural products have resulted in increases in production, savings on labor and further specialisation and intensification. The mixed farming systems, which were especially common on sandy soils, disappeared, and currently 90% of all dairy farming is concentrated on specialized farms (Aarts & Van Gorp, 1989).

Lantinga & Rabbinge (1996) plead for 'a renaissance' of mixed farming systems to reduce the use of external inputs and increase the efficiency of external inputs by

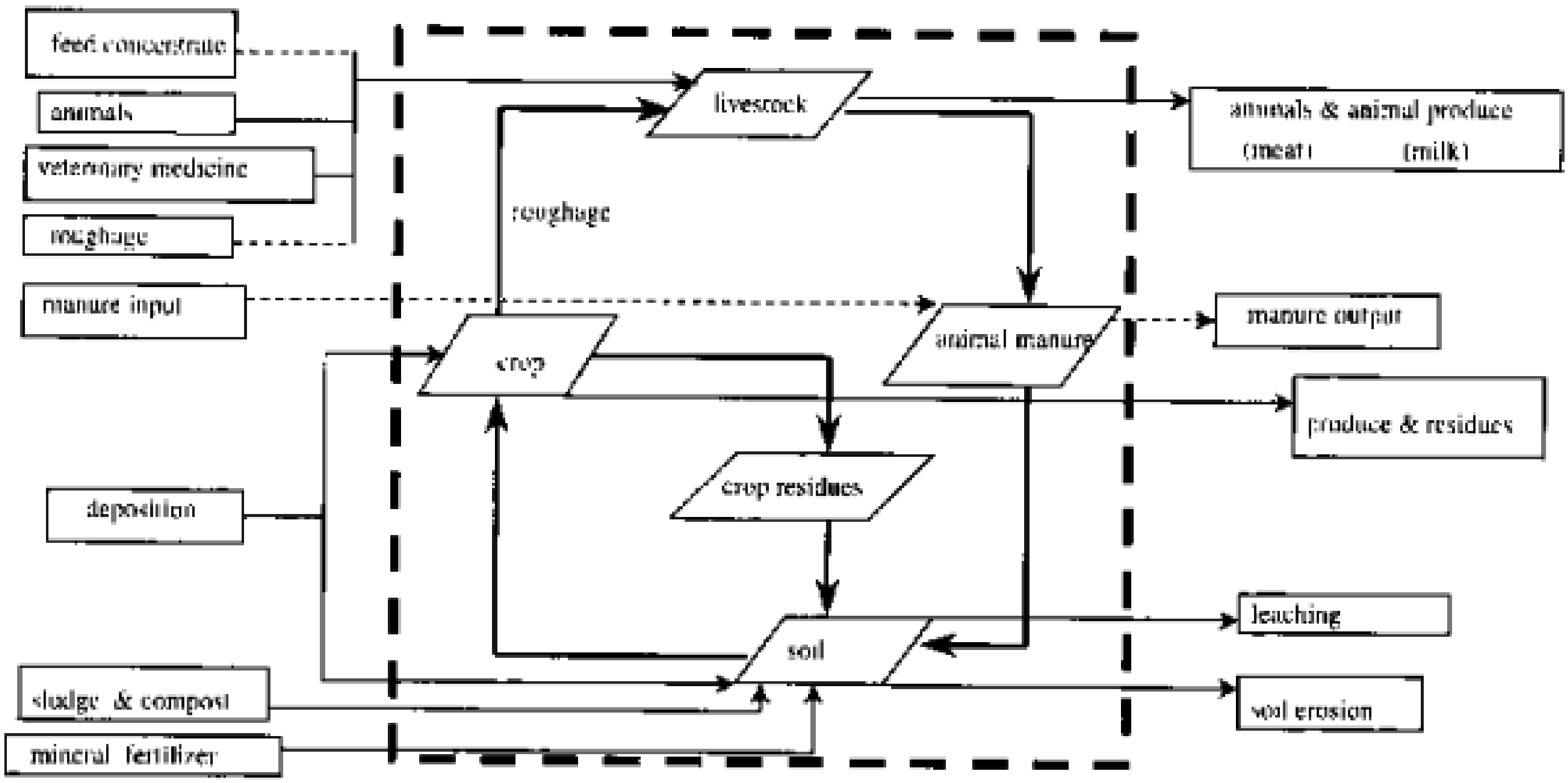

Figure 6. Mixed farming system; input, internal (heavy solid arrows), and output flows.

recycling of plant and animal products. Moreover, labor may be better utilized and income risks spread. Another motive for re-integration is the lack of perspectives for current arable farming systems in the Netherlands (Anonymous, 1992). More viable farming types could be developed by mixing arable farming with intensive husbandry or dairy farming systems, either within a single farm or on a regional scale.

By mixing land-bound farming systems (i.e., arable and dairy farming), substance cycles could be closed by the exchange of forage crops with manure, and crop rotations could be widened which would result in less diseases and the potential for growing more profitable crops. Model studies indicate that this combination may improve both economic and ecological results (De Koeijer *et al.*, 1995). On experimental farm 'The Minderhoudhoeve' (near Swifterbant in the Flevopolder: 52° 33′ N, 5° 40′ E), two different mixed farming systems of this type are being developed: an integrated farm (135 ha) and an ecological farm (90 ha). Further details on the research plan of both mixed farms are provided in Lantinga & Van Laar (1997). We calculated heavy-metal balances at the farm and field level based on the input, output, and internal flows as described in this research plan. Additional information on crop yields was found in Aarts (1991) and Roeterdink & Haaksma (1993). Literature data were used on heavy metals in atmospheric deposition (Aben *et al.*, 1992), leachate (Breimer & Smilde, 1986; Ferdinandus *et al.*, 1989 Van Erp & Van Lune 1991; Boumans & Wessels, 1993; Van Duivenboden *et al.*, 1995), mineral fertilizers (Van Erp & Meeuwissen, 1994; De Boo, 1995; Driessen & Roos, 1996), animal manure (Driessen & Roos, 1996), source-separated organics (SSO) compost (Van Erp & Evers, NMI, pers. comm.), concentrates (Anonymous, 1994), meat (De Boo, 1995), milk (Anonymous, 1985; Anonymous, 1990), arable crops (Van Erp & Meeuwissen, 1994; De Boo, 1995), grass, and feed crops (Anonymous, 1985; Van Erp & Meeuwissen, 1994; De Boo, 1995). Runoff, offtake with soil adhering to crops, and soil ingestion by cows were not accounted for. A detailed description of the calculations is given in Opschoor (1996).

The farm-gate balance of the integrated mixed farming system is shown in Table 7. The internal flows in the integrated mixed farming system consist of cow manure and roughage (grass, clover, fodder beets, silage maize). These flows are not part of the farm-gate balance, but they are important for the field-scale balance (Table 8).

On mixed farms, part of the land is grassland and part is used for growing arable and forage crops. The integrated farm comprises 41 ha grassland and 94 ha arable land. We derived separate field-scale balances for grassland and arable land. Grassland is amended with N-fertilizer and manure (52 ton ha^{-1}). The grass/clover mixture receives 18 ton manure per ha. Table 9 shows the heavy-metal balances for the grassland.

Arable land is amended with about the same amount of N-fertilizer as grassland and with P-fertilizer and manure. Table 10 shows the heavy-metal balances for the

Table 7. Farm-gate balance sheets of heavy metals (g ha^{-1} yr^{-1}) of the integrated mixed farming system at the Minderhoudhoeve.

	Cd	Cu	Pb	Zn
Input (I):				
Mineral fertilizers	1.37	1.2	1.5	16.2
Feed concentrates	0.05	16.5	0.5	52.8
Deposition	1.3	25.6	33.1	156.0
Total	2.72	43.3	35.1	225.0
Output (O):				
Crops	0.66	25.7	3.9	101.1
Milk	0.007	0.2	0.03	21.6
Meat/animal	0.0007	0.4	0.002	6.4
Leaching	1.6	43.1	14.8	63.3
Total	2.3	69.4	18.7	192.4
I-O	0.42	-26.1	16.4	32.6

Table 8. Total (grassland and arable land combined) field-scale balance sheet (g ha^{-1} yr^{-1}) of the integrated mixed farming system at the Minderhoudhoeve.

	Cd	Cu	Pb	Zn
Input (I):				
Fertilizers/manure	2.2	132.9	54.2	543.3
Deposition	1.3	25.6	33.1	156.0
Total	3.5	158.5	87.3	699.3
Output (O):				
Arable crops	0.66	25.7	3.9	101.1
Grass & forage crops	1.1	62.8	12	665.4
Leaching	1.6	43.1	14.8	63.3
Total	3.4	131.6	30.7	829.8
I-O	0.1	26.9	56.6	131

Table 9. Field-scale balance sheet (g ha^{-1} yr^{-1}) of grassland of the integrated mixed farming system at the Minderhoudhoeve.

	Cd	Cu	Pb	Zn
Input (I):				
Fertilizers/manure	2.4	219.1	89.6	876
Deposition	1.3	25.6	33.1	156
Total	3.7	244.7	122.7	1032
Output (O):				
Grass offtake	1.4	161.6	27.4	1378
Leaching	1.6	43.1	14.8	63.3
Total	3.0	204.7	42.2	1441.3
I-O	0.7	40.0	80.5	409

arable land. Heavy-metal balances may be calculated for the livestock compartment as well (Table 11).

In the ecological mixed farming system, SSO-compost provides half the required P-input. The farm-gate balance of the ecological mixed farming system is shown in Table 12. Almost all arable and forage crops are used for animal feed, hence crop offtake is restricted to 6 ha root crops. The field-scale balance of the ecological mixed farming system is shown in Table 13. Internal flows consist of cow manure and practically all crops.

Comparisons

Arable farming

Regarding total Cd input to the Nagele experimental farm, only for CAFS-MF is ad-

Table 10. Field-scale balance sheet (g ha^{-1} yr^{-1}) of arable land of the integrated mixed farming system at the Minderhoudhoeve.

	Cd	Cu	Pb	Zn
Input (I):				
Fertilizers/manure	2.1	95.4	38.7	387.5
Deposition	1.3	25.6	33.1	156.0
Total	3.4	121.0	71.8	543.5
Output (O):				
Feed crops	0.95	19.7	5.2	354.5
Arable crops	0.65	25.7	3.9	101.1
Leaching	1.6	43.1	14.8	63.3
Total	3.2	88.5	23.9	518.9
I-O	0.2	32.5	47.9	24.6

Table 11. Heavy-metal balance sheet (g) of the livestock compartment in the integrated mixed farming system at the Minderhoudhoeve.

	Cd	Cu	Pb	Zn
Input (I):				
Concentrates	7	2226	74	7122
Roughage	146	8476	1618	89826
Total	153	10702	1692	96948
Output (O):				
Milk	1	27	4	2914
Animal/meat	0.1	49	0.2	863
Manure	107	17790	7116	71160
Total	108	17866	7120	74937
I-O (g)	45	7164	5428	22011
I-O (g cow^{-1})	0.24	37.7	28.6	116
I-O (g ha^{-1})	0.33	53.1	-40.2	163

Table 12. Farm-gate balance sheet (g ha^{-1} yr^{-1}) of the ecological mixed farming system at the Minderhoudhoeve.

	Cd	Cu	Pb	Zn
Input (I):				
Mineral fertilizers	0.03	2.7	3.0	8.9
SSO-compost	1.7	83	198	489
Concentrates				-
Deposition	1.3	25.6	33.1	156.0
Total	3.03	111.3	234.1	653.9
Output (O):				
Crop produce	0.36	17.6	1.4	253.8
Milk		0.18	0.02	19.3
Meat/animals		0.36	-	6.4
Leaching	1.6	43.1	14.8	63.3
Total	2.0	61.2	16.2	342.8
I-O	1.0	50.1	218	311

dition through atmospheric deposition lower than addition through fertilization (Figure 2a). The Cd budget of CAFS-MF shows a much larger accumulation than for CAFS-OF due to the Cd inputs with triple superphosphate applications. Copper and Zn inputs are highest when animal manures are applied and the contribution of atmospheric deposition only exceeds that of fertilizer in CAFS-MF (Figures 2b and 2d).

Cultivation of crops with a high Cd offtake (carrots, sugar beets, ware potatoes and onions) also influences the Cd balance. EAFS has a higher Cd input/output ratio than IAFS and CAFS-OF because a larger percentage of the total area is taken up by

Table 13. Total (grassland and arable land combined) field-scale balance sheet (g ha^{-1} yr^{-1}) of the ecological mixed farming system at the Minderhoudhoeve.

	Cd	Cu	Pb	Zn
Input (I):				
Mineral fertilizers	0.03	2.7	3.0	8.9
SSO-compost	1.7	83	198	489
Animal manure	0.6	100.0	40.0	400.0
Deposition	1.3	25.6	33.1	156.0
Total	3.63	211.3	274.1	1053.9
Output (O):				
Crop offtake (all)	1.5	100.7	13.6	999.1
Leaching	1.6	43.1	14.8	63.3
Total	3.1	143.8	28.4	1062.4
I-O	0.53	67.5	246	8.5

grain crops with limited Cd offtake. Also, inputs via manure are higher in EAFS, partly due to large applications to raise the P status of the soil.

Clearly, crop rotation and the selection of fertilizers directly influence the heavy-metal balance of arable farming systems. Optimization models may be used to formulate fertilizer plans that meet constraints on heavy-metal input via fertilizers, but also on other agricultural, legislative and economic constraints, based on farm-specific information. Velthof *et al.* (1996) using such an optimization model for arable farming, indicated that it is not possible to formulate fertilizer plans in which input and output balance for Cd, Cu and Zn concurrently. Minimizing Cd input increases Cu and Zn inputs and minimizing Cu and Zn inputs increases Cd input due to substitution between animal manure and mineral fertilizer. This is also shown in the Nagele study. The integrated system compares favorably with the conventional (MF) system with respect to Cd, but the reverse holds for Cu, Pb and Zn, mainly due to different fertilizers used in these systems.

Based on recent measurements of heavy-metal contents in different kinds of fertilizers, manures and composts, Anonymous (1997) calculated the heavy-metal balances for arable farming on a clay soil (50% grains, 25% potatoes, 25% sugar beet) with different fertilizer plans (cattle, pig and broiler manure, compost, mineral fertilizers) representative of Dutch arable farming. Comparing the results of Nagele experimental farm with some scenarios by Anonymous (1997) shows that EAFS and CAFS-MF have a comparable Cd surplus for comparable fertilizer plans. Cadmium depletion only occurs in IAFS and CAFS-OF (no mineral P-fertilizer and less manure applied). Depletion of Cu and Zn is comparable for CAFS-MF and the fertilizer plans with mineral fertilizers only. However, Cu and Zn surplusses in the animal manure scenarios are much higher than those of Nagele farm due to the other types of fertilizers used (pig manure and compost) and the higher amounts applied. The Pb balances are similar in both studies.

Dairy farming

In dairy farming systems, the role of feed management is very important, but the effects on the heavy-metal balance may not always be straightforward.

The proportion of forage produced on-farm should be maximized to restrict the need for purchased feeds, with its external inputs of minerals and heavy metals. However, the quantity and quality of roughage produced is not sufficient to satisfy the total feed demand, and therefore concentrates are imported. Growing concentrate substitutes on-farm may result in less grassland available for roughage production, which results in more intensive grassland use (i.e., higher N-levels) to secure a sufficient roughage supply. Hence, growing concentrate substitutes does not necessarily result in lower heavy-metal inputs. If the land is suitable for growing both grass and concentrate substitutes, land allocation to the different crops may be optimized, taking into account both the desired quantities and qualities of forages, and the possibility to apply animal manure.

Mixed farming

Comparing Tables 7 and 12, shows that input with SSO-compost in the ecological system far exceeds the combined input with fertilizers and concentrates in the integrated system.

Tables 9 and 10 show for Cu, Pb and Zn in the integrated system that both the input in fertilizers and the output in crop products is (much) larger on grassland than on arable land. The balances show a larger Cd, Cu, and Pb surplus for grassland than for arable land. On arable land, Zn accumulates and on grassland Zn depletion occurs.

It should be noted that for both the ecological farm and the integrated farm a discrepancy exists between the farm-gate balance and the total field-scale balance (Tables 7 and 8; Tables 12 and 13). Since the heavy metals do not degrade or volatilize, the difference must be visible in the livestock compartment (Table 11). This is discussed in the next section on uncertainties.

Uncertainties

For effective heavy-metal management and strategic decision making, insight is needed into the relationships and uncertainties in the balance calculations. In the case of deterministic variables, there is no uncertainty associated with a certain value. Calculations according to the static and dynamic balances were carried out deterministically, while in reality the values of G, A, L, and U vary and should thus be considered uncertain. The following discussion of the balance in the livestock compartment, leaching and SSO-compost illustrate some uncertainties involved.

Livestock compartment balance

The heavy-metal balance of the livestock compartment in the integrated mixed farming system (Table 11) shows inconsistencies. According to the calculations, Cd and Zn accumulate in the cows in relatively large amounts, while Cu and Pb seem to be 'produced' by the cows. This discrepancy between the internal flows from animal to crop and from crop to animal may have several causes:

- The literature based (i.e., average) heavy-metal contents of concentrates and roughage are too low for Cu and Pb and too high for Cd and Zn;
- The literature based (i.e., average) heavy-metal contents of animal (cow) manure are too high for Cu and Pb and too low for Cd and Zn;
- Significant Cu and Pb inputs may have been overlooked e.g. from diffuse heavy-metal sources in extra feed additives, stable components and machinery, plumbing and water piping, soil ingestion, etc.;
- A combination of these three causes.

The heavy-metal contents in feedstuff and manure show large variations. Hence, it is risky to use averaged or literature values only. On-farm monitoring is needed to enable reliable on-site quantification.

Reiner *et al.* (1996) point to the possibilities to improve on-farm heavy-metal management by checking metal inputs from diffuse sources, e.g. corrosion of piping. Soil ingestion may be important in the dietary intake of trace elements by grazing animals. For example, the size of this flow depends on grazing behavior, stocking density, soil type, weather conditions, season, length of the grass and type of grass (Van Hooft, 1995). Where land is contaminated with elements of low availability to pasture, cattle may ingest up to 10 times the amount of the elements in the form of soil than that in herbage. Thus, the soil-animal flow may complement, or override the soil-plant-animal flow (Thornton, 1981). In the literature (Van Hooft, 1995) soil ingestion values from 100 to 900 (g d^{-1}), with a mean value of 427 ± 227, have been recorded. Lexmond (1992) stated that soil may comprise 1 (dry year) to 2% (wet year) of total dry matter intake. Thus, soil ingestion by animals and subsequent excretion in manure results in an internal cycle and internal redistribution of soil and metals.

Based on an average soil intake of 200 kg yr^{-1} and assuming heavy-metal soil contents at the Minderhoudhoeve similar to those at Nagele, the heavy-metal intake due to soil ingestion during grazing is ca. 100 mg, 5 g, 7 g, and 20 g for Cd, Cu, Pb, and Zn, respectively. Roughage, containing soil, may be another source of extra heavy-metal intake. However, heavy-metal intake from these sources does not account for the observed depletion of Cu and Pb. A combination of the possible causes for the discrepancies is therefore most likely.

Leaching

Reliable leaching data are both important and scarce. We derived adsorption models for the Nagele soil. For their interpretation, it is important to realize that the laboratory work does not resemble field circumstances exactly. For the Minderhoudhoeve systems, we used an average leaching rate based on literature values resulting in ranges of 0.5–2.8, 5–87, 4–35, and 2.6–88 g ha^{-1} yr^{-1} for Cd, Cu, Pb, and Zn, respectively. Using the extremes of these ranges, instead of the average number, changes the balances significantly.

SSO-compost

Tables 12 and 13 show that the heavy-metal inputs associated with the use of SSO-compost are very high on the ecological mixed farm of the Minderhoudhoeve. The compost inputs were based on average values of heavy-metal contents in SSO-compost. If compost with higher or lower contents were used, the balances would differ significantly. Moreover, regular SSO-compost applications result in long-term changes in clay and organic matter contents which may considerably influence the heavy-metal contents in the course of time (Moolenaar *et al.*, 1997a).

Conclusions and recommendations

This study of heavy-metal balances in different agro-ecosystems in the Netherlands shows different heavy-metal input, output and accumulation patterns for different metals among and within the farming systems. Hence, specific analyses for each farming system are needed in addition to studying the total agricultural sector, as performed by statistical offices (e.g. Van Eerdt & Stiggelbout, 1992).

Experimental farms are valuable resources for studying heavy-metal flows by measuring metal transfers at these sites. Integral monitoring of mineral, biocide, and heavy-metal flows at the farm gate is recommended to define options for developing sustainable management of agro-ecosystems.

Field-scale balances enable field specific and dynamic analyses of heavy-metal accumulation, leaching and uptake, and allow identification of 'hot spots' (e.g. specific fields, crops, applications). Moreover, analyses on field scale enable elucidation of the role of internal cycles and quantification of soil-bound flows like dirt tare and erosion. The 'total field balance' really does not exist for mixed farms considering the differences between grassland and arable land. If large differences exist among fields due to individual treatments or specific processes, large discrepancies may be expected between farm-gate and field-scale balances.

An important issue in heavy-metal balance research is the lack of suitable methods to quantify leaching from the plough layer. Samples from drains do not reflect the situation just below the plough layer. Information from adsorption experiments is difficult to extrapolate to field situations and is not related to the actual water flux. This also holds for pore water analyses which moreover only give an instantaneous impression of solute concentrations. Concurrent measurement of solute concentration (proportional solute sampling) and water flux just below the plough layer (water retention characteristics) would result in the most reliable leaching data.

Mixed farming systems compare favorably with specialized (arable or dairy) farming systems with regard to heavy-metal accumulation. Due to the internal cycling of forage and manure, less external inputs are required and thus import of heavy-metal containing raw materials and products is minimized. Mixed farming need not be restricted to farm level. Optimization of energy and material use and minimization of waste production may be enhanced by 'mixed farming' at regional level. In that case, different types of enterprises (agricultural, industrial, recycling) should collaborate strategically to use effluents of one process as input for another.

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