Nutrient and Trace Element Flows and Balances at the Öjebyn Dairy Farm

Aspects of Temporal and Spatial Variation and Management Practices

Helena Bengtsson
Faculty of Natural Resources and Agricultural Sciences
Department of Soil Sciences
Uppsala

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Abstract

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A better understanding of on-farm element flows is required to reduce element imbalances leading to either high element loads or deficiencies in arable soils. Element balance calculations at farm/field level can be a tool for evaluation of farming systems, both from an environmental and from sustainable nutrient management perspective. The overall aim of the present thesis was to contribute to the development of element balances as a sustainability tool. The work included evaluation of different aspects of uncertainty associated with element balance calculations, in order to provide a better basis for the interpretation. The Öjebyn dairy farm (65°21'N, 21°24'E) where organic and conventional production had been practiced in paralell since 1988 was used as a case study. The main objective was to study macronutrient (N, P, K, Mg) and trace element (Cd, Cu, Zn) flows and balances at farm-gate, barn and field level during a 3- to 5-year period in organic and conventional dairy production. By monitoring nutrient balances at different scales it was possible to quantify the internal flows and to identify sinks and sources not revealed by determining nutrient balances at farm-gate alone. At field level, the element imbalances of most concern were negative K balances in the organic system (–17 kg ha^{-1} yr^{-1}) and positive Cd and Zn balances in the organic respective conventional system (0.35-0.52 g ha^{-1} yr^{-1} and 295-449 g ha^{-1} yr^{-1}). The temporal and spatial variation was large and influenced the outcome and the interpretation of the balance calculation. It was also demonstrated that spatial variation, in terms of local soil characteristics, had to be considered in the comparisons between two farming systems. In many cases the calculated error in the element concentration contributed to the uncertainty in the field flows to the same extent as the amount of material (*e.g.* biomass). The metal balance was shown to be estimated with least precision *e.g.* due to large variation in the water run-off flow. Generally, to increase the accuracy and usefulness of element balances farm-specific data should be used for home-produced feed and manure/urine. To include the variation in the balance calculation should be a standard part of element balance calculation procedure.

Key words: Farm-gate balance, field balance, dairy farming, nutrient management, organic farming, trace metal, leaching, surface run-off, sustainability, uncertainty

Author´s address: Helena Bengtsson, Department of Soil Sciences, SLU, Box 7014, SE-750 07 Uppsala, Sweden. E-mail: helena.bengtsson@mv.slu.se.

Till Irma och Iris

Contents

Preface

Papers I-IV

This thesis is based on the following papers, which are referred to in the text by their Roman numerals:

I. Bengtsson, H., Öborn, I., Jonsson, S, Nilsson, I. & Andersson, A. 2003. Field balances of some mineral nutrients and trace elements in organic and conventional dairy farming – a case study at Öjebyn, Sweden. *European Journal of Agronomy 20*, 101-116.

II. Bengtsson, H., Jonsson, S. & Öborn, I. Variation in element flows and field balances – a three-year case study in organic and conventional dairy systems at the Öjebyn Farm. (Submitted to *Nutrient Cycling in Agroecosystems*)

III. Bengtsson, H., Alvenäs, G., Nilsson, S.I., Hultman, B. &. Öborn, I. Cadmium, copper and zinc leaching and surface run-off losses at the Öjebyn farm in Northern Sweden – temporal and spatial variation. (*Submitted to Agriculture, Ecosystems and Environment*)

IV. Öborn, I., Modin-Edman, A-K, Bengtsson, H., Gustafson, G.M., Salomon, E., Nilsson, S.I., Holmqvist, J., Jonsson, S. & Sverdrup, H. A systems approach to assess farm scale nutrient and trace element dynamics – A case study at Öjebyn dairy farm. (Submitted to *AMBIO: A Journal of the Human Environment*)

Photo coverpage : The Öjebyn farm. Taken by Gustav Sohlenius

Introduction

Agroecosystems differ from most natural ecosystems by higher flows of inputs and outputs (Van Noordwijk, 1999). Nutrient inputs in the form of fertilisers and animal feeds are crucial in modern agriculture to supplement native nutrient pools and to support greater crop and animal production. Agricultural systems with imbalances in terms of high element surpluses or nutrient deficiencies are not sustainable in the long term. If the external inputs lead to high surpluses, the risks for losses to the surrounding environment increase, or the surplus will accumulate in the soil. Excess nitrogen (N) or phosphorus (P) will create an increased risk of losses through gaseous emissions (N), surface run-off or leaching (N and P) to aquatic systems. When fertiliser application are dominated by N, there is a risk of *e.g.* potassium (K) deficiency (Alfaro *et al*., 2003), especially in areas dominated by coarse-textured soils (Askegaard *et al*., 2004). Long-term accumulation of trace metals in an arable ecosystem may negatively affect soil fertility, product quality and leaching to other ecosystems (Ross, 1994).

Many agricultural systems have substantial surpluses of nutrients, especially those involved in livestock production (Jarvis, 2000). The general trend in the temperate agricultural systems in Europe is towards increased livestock density leading to concerns about the environmental impacts of nutrient losses from farms and farmland. Nutrient use efficiency, defined as the percentage of outgoing over incoming nutrients, can be seen as one indicator of the sustainability of nutrient management practices (Scholefield & Smith, 1996). Nitrogen and P use efficiency has been shown to be lower in dairy than in arable (cereal) and pig production systems (Domburg *et al*., 2000). In Sweden the dairy farms represents approximatly 30%, of the total amount of agricultural production holdings (SCB, 2004).

There are increasing concerns about soil fertility and the risks of nutrient deficiencies in the crop production in extensive agricultural production systems, including a major proportion of organic farming systems. The limited scope for importing nutrients to organic farms can make balancing inflows against outflows difficult, which may result in nutrient imbalances and deficiencies (Watson *et al*., 2002). In Europe, 2% of arable land is in organic cultivation (IFOAM, 2004). The corresponding amount in Sweden is 16% of arable land (SCB, 2004). The main driving factors for the change to organic farming are a growing market for organic produce as well as political support.

The situation with element loading or nutrient deficiencies in many arable soils requires a better understanding of the on-farm element flows. Element balance calculations at farm/field level can be a tool for evaluation of different farming systems from an environmental perspective (risks for emissions from agriculture) and a sustainable nutrient management perspective (Janssen, 1999; Moolenaar & Lexmond, 1999; Watson *et al*., 2002; Öborn *et al*., 2003). Balances of both nutrients and trace metals for different types of agricultural systems can be used to gain insights into the long-term development of soil quality and thus the sustainability of the system. The balance calculation tool has become widely used by policy-makers, extension workers (advisors), certification organisations and farmers as an instrument for planning and control of on-farm nutrient management directed towards more sustainable agricultural production (Brouwer, 1998; Goodlass *et al*., 2003). From this aspect, it is important to evaluate the accuracy of the element balances, and the consequences of uncertainties in inflow and outflow esimates (Oenema *et al*., 2003). To enable the use of element balances as performance indicators within and across farms, there is a clear need for standardised methodology, specifying which flows should be included in a farm or field balance and how these flows should be estimated (Oenema *et al*., 2003). This also requires improved understanding of the spatial and temporal variation in the different inflows and outflows (Watson & Atkinson, 1999).

Objectives

The overall aim of the present thesis was to contribute to the development of element balance calculations as a sustainability tool. This included: improving and evaluating different aspects of uncertainty associated with element balance calculation; providing a better basis for the interpretation of element balances; and addressing some sustainability aspects in connection with management practices and scale issues in balance calculations. The Öjebyn farm was used as a case study for the investigations.

The main objective was to study macronutrient (N, P, K, Mg) and trace element (Cd, Cu, Zn) flows and balances over a 3- to 5-year period in organic (org) and conventional (conv) dairy production at the Öjebyn farm. The specific objectives were:

(1) To *quantify* pools, flows and balances at farm and field scale and to assess the degree of imbalances in the element flows.
(2) To determine the importance of the temporal and spatial *variation* in the different field flows and balances.
(3) To address the *sustainability aspects* in terms of i) product quality; ii) accumulation/depletion in the soil; and iii) losses of trace metals to the surrounding environment via water run-off.

The starting premises for the investigations were that:

- Knowledge about variation in the different input and output flows adds important information in the interpretation of the element balance calculation.
- It is important to include site-specific information in system comparisons and in element balance calculations.
- Element balance calculations can be valuable concept in relation to sustainability.

The element balance calculation can be used for different purposes, including environmental perspectives (risks for emissions from agriculture) and sustainable nutrient management perspectives. In this thesis, the focus is on both those purposes. Nitrogen, P, K and magnesium (Mg) were studied in order to assess nutrient use efficiency from a crop production and environmental perspective. The trace elements cadmium (Cd), copper (Cu) and zinc (Zn) were chosen because of their potential effect on crop quality and soil fertility. These metals have potential toxicological impacts, with Cd posing a health risk for humans via food intake (cereals, root crops and vegetables), while high concentrations of Cu and Zn may interfere with ecosystem functioning, such as reducing the rate of soil organic matter decomposition or nitrogen fixation (Giller *et al*., 1998).

The work reported in this thesis formed part of a research project within the FOOD 21 – Sustainable Food Production - Programme. Within this programme, research projects, systems analysis and scenarios are being developed across the entire food chain from 'plough to plate', including crop and animal production, animal welfare, food quality, farmers' decision making and social conditions, consumer attitudes and behaviour, food processing and transport (Bylund *et al*., 1997).

Background

Definitions and aspects of element balances

What is an element balance?

In this context an element balance is a mass balance, including inflows and outflows to a system, that is used to assess the degree of element balance/imbalance in the system. The elements considered are macro nutrients and trace elements that are either micronutrients and/or potential toxic elements, and the systems are agricultural systems at farm or field level. With a positive nutrient balance the element may build up in the soil, and/or potentially be lost from the system through emissions to air or to surface run-off or groundwater. The element balance at this stage is defined as:

Σ Element inflows – Σ Element outflows = (Eq 1)
Change in total element stored within/potentially lost from the system.

Mass flow balances are usually established for a defined system on an annual basis and can be calculated for different scales, *e.g.* national, region, farm or field (Oenema & Heinen, 1999; Watson & Atkinson, 1999; Öborn *et al*., 2003). Figure 1 shows the nutrient flows and balances on a dairy farm at three different scales (Paper IV). *Farm-gate balances* include purchased and sold products. They are easy to establish since mass flows following cash flows are often well documented. The farm-gate balance gives a first indication of probable element imbalances on farm level. However, it is not complete since inputs and outputs not passing the farm-gate are not included *i.e.* N-fixation, atmospheric deposition and leaching. *Barn balances* are sub-system balances including feed-animal manure/animal products. The barn balance could show the relationship between home-produced and purchased feed inputs. *Field balances,* or soil surface balances, include 'bio-physical flows' and may also in contrast to Eq 1 include 'diffuse inflows', such as atmospheric deposition and biological nitrogen fixation, and losses, such as gaseous emissions, leaching and run-off, which can be difficult to quantify. The field balance can be related to the existing soil pools and give an indication of risks of soil accumulation/depletion. In farming systems based on animal production, there is a large internal circulation, with flows of elements through soil-crops-animals-manure-soil.

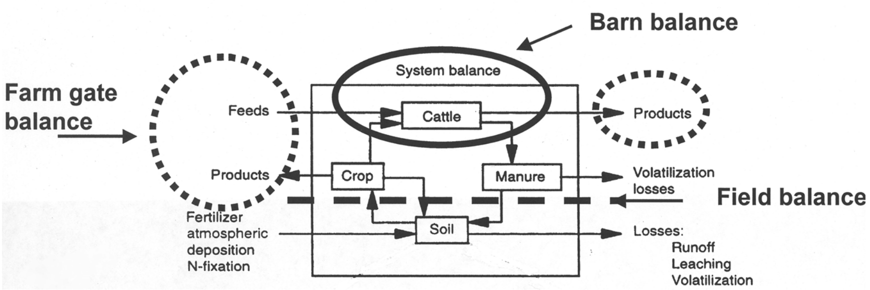

Figure 1. Schematic illustration of nutrient flows on a dairy farm. Three different approaches for nutrient balances were applied; Farm gate (▪▪▪▪), Barn (▬▬), and Field balances (▬ ▬) (modified from Oenema & Heinen, 1999).

Element balances have mainly been calculated for macronutrients (N, P and K) (Goodlass *et al*., 2003). However, the balance approach has proven useful not only in soil fertility studies for macronutrients, but also in soil pollution studies, for instance in studies of risks of trace metal accumulation in agricultural soils (Andersson, 1992; Moolenaar & Lexmond, 1999).

Why use balance calculations?

Element balance calculations provide indications of the trends in soil fertility changes. The heterogeneity of soils as well as the large soil pools makes it difficult to distinguish small alterations with time in the concentrations and amounts of elements by means of repeated soil sampling and analyses. Even though a net inflow of an element may exist, current soil tests give little indication of the rate of element accumulation. Small alterations may be harmless in a short-term perspective but may be risky in a longer perspective. 100 years is the time perspective often used when talking about sustainable agroecosystems (Andersson, 1992). A more sensitive method to reveal weak current time trends of changes in the soil pool is to establish the degree of imbalance between supply and removal of the element of interest.

The element balance calculation can be very illustrative and the results are easy to communicate. Nutrient balances can be a helpful indicator in nutrient management for the farmers. Furthermore, the element balances can be an agro-environmental indicator and can serve to raise awareness of potential negative effects on the surrounding environment for policy-makers. Scoones & Toulmin (1998) stress that rather than seeing element balance results as definitive they should be used as the basis for ongoing policy and management dialogue.

Element balance calculations and their practical use - national and international

Nutrient balances have been calculated with different approaches for both high input and low input systems (*e.g*. Smaling *et al*., 1999). In African assessments, nutrient flows and balances have been used to determine the nutrient requirements of sustainable crop production at spatial levels, from the field scale to African sub-continents (Smaling *et al*., 1993; Stoorvogel *et al*., 1993). Nutrient balances calculated for N, P and sometimes for K differ widely but mostly converge to negative balances (Schlecht & Hiernaux, 2004). In countries with modern intensive agriculture, nutrient surpluses are often found. In recent times, some of the large input flows to agro-ecosystem have been reduced, *e.g*. metal atmospheric deposition, N and P application due to increasing concerns about over-fertilisation, and Cd input via mineral fertilisers due to use of apatite-based phosphates which are generally low in Cd. Still many agricultural systems have high element surpluses. Nutrient surpluses have been observed in detailed livestock farm level balance calculation investigations in the UK (Jarvis, 1993; Haygarth *et al*., 1998), in the Netherlands (Aarts *et al*., 2000; Van Keulen *et al*., 2000), in Denmark (Halberg, 1999) and in Sweden (Fagerberg *et al*., 1996). The study at the Öjebyn farm represented a system with low input and output flows compared to the cited investigations.

Trace element balances have been calculated with less frequency than macronutrient balances, and those presented have mostly been for national or regional conditions or high input systems (Van Driel & Smilde 1990; Andersson, 1992; Moolenaar & Lexmond 1998; Poulsen, 1998; Keller *et al*., 2002; Keller & Schulin, 2003).

Within Europe, several computer-based accounting systems for plant nutrients have been developed (Goodlass *et al*., 2003). Simple nutrient balances are becoming widely used by advisors and certification organisations as tools for planning and as performance indicators. In the Netherlands, farm-gate balances, in combination with levies when a certain target surplus is exceeded, are used as a policy tool (MINAS) to decrease N and P leaching to groundwater and surface water (Onderstijn *et al*., 2003; Hanegraaf & Den Boer, 2003). For heavy metals this has not yet been achieved (Römkens *et al*., 2003). In Sweden, the nutrient accounting model STANK is used for on-farm planning and monitoring of nutrient management (Linder, 2001). The model is developed as an advisory tool for farmers and extension workers and the overall aim is to increase the nutrient use efficiency at the farm level and hence reduce the risks for losses.

These rather simple models do not treat the pools and flows of nutrients in a dynamic manner and the length of each simulation is generally limited to one year (*e.g*. Goodlass *et al*., 2003). The internal flows of nutrients can be substantial, especially on farms with livestock, and the importance of including these flows in the balance calculations has been stressed (Zacchero *et al*., 1997; Gustafson *et al*., 2003; Öborn *et al*., 2003).

Uncertainties of an element balance calculation

The wide use of element balances highlights the need for improved accuracy of the balance calculations. To be able to interpret balance calculations one has to know the effects of the uncertainty in inputs and outputs on the surplus or deficit. The uncertainties in currently performed balance calculations are merged in the difference between inflows and outflows, *i.e*. the balance term. Aiming at systems with lower input and output flows brings about an urgent need for better estimation of the accuracy of the element balance calculation.

Oenema *et al*. (2003) suggested a way of classifying uncertainties in nutrient balances by distinguishing between *fundamental uncertainties* related to the structure and presentation of the balance and *operational uncertainty* related to uncertainty in the data and parameters. There are no specific rules concerning which flows a farm and field balance should include, which causes difficulties when the results of element balances are compared across farms. Furthermore, the delineation of system boundaries in both space and time is a critical step in the compilation of element balances. The balance calculation is an easy method to use but for the usefulness of the outcome, the quality of the data used is a key factor. Data used in element balances are often based on a combination of different origin/type (primary data, estimates, assumptions) and thereby come from different sources and are collected at different frequencies (Oenema *et al*., 2003). Uncertainty in data input and parameters arise from i) lack of data and knowledge, ii) spatial and temporal variability at different scales and iii) change in items and parameters with time. The temporal and spatial variability can be defined as sampling and measurement errors (*e.g*. random variation leading to a confidence interval around the mean balance) as well as system errors which refer to inherent differences between fields at the farm. The soil system is characterised by an inherent variability at small spatial scales. In this study when temporal and spatial variation is discussed it refers to a combination of the two last items, ii) and iii), in the definition of operational uncertainty.

Uncertainties in element balance estimates may lead to a wrong interpretation of the balance. Generally there is little quantitative information available about uncertainties (error range) in the overall balance (Oenema *et al*., 2003). It is common that the uncertainty is simply ignored. There is therefore need for standard procedures and guidelines in element balance calculations and uncertainty analyses, to improve the confidence in and applicability of this tool (Oenema *et al*., 2003).

Mulier *et al*. (2003) reported the results from N and P inflows and outflows for one year at nine dairy farms in Belgium. They compared possible maximum errors for different input and output flows in a farm-gate balance using either standard values or having them analysed. The error associated with estimates or actual determinations of either inflow quantities of manure or outflow quantities of plant products were 10-15% and 5%. The analysed nutrient content in the manure had a variation of 10%, while if standard values were used there was a variation of 30%. The analysed nutrient content in the plant products were 10% and if standard values were used there were a variation of 20%. There was a rather big error on most farms linked to manure due to the wide variation in its nutrient concentration, when using fixed values.

Materials and Methods

Description of the study site

The Öjebyn Farm

This study was carried out at the Öjebyn experimental farm, situated in north-eastern Sweden (65°21'N, 21°24'E) on the west-coast of the Bay of Bothnia (Figure 2). The average annual precipitation is 500 mm and the mean air temperature 2.1°C (SMHI, 2004). The farm has a long tradition of milk production (more than 100 consecutive years). In 1988, the farm was split into two units, enabling a full-scale comparison between organic and conventional production, with 40-50 dairy cows in each system (Jonsson, 2004). The farm has 105 ha of agricultural land, 58 ha managed within the organic system and 47 ha within the conventional system. A six-year crop rotation is used, including a mixed crop of oats and pea (forage crop), 3 years of grass/clover ley (ley I-III), spring barley and potato (Figure 3). All crops are represented on the farm every year in both farming

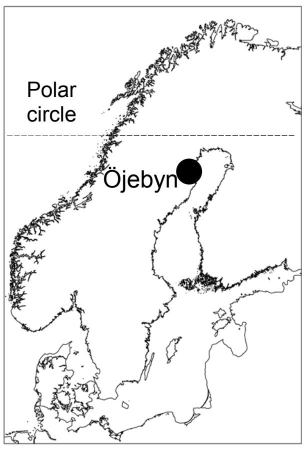

Figure 2. Location of the Öjebyn experimental farm (65°21'N, 21°24'E) in Sweden.

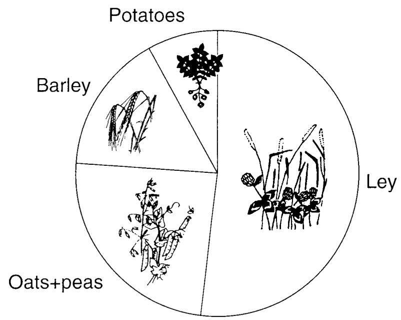

Figure 3. The crop distribution at the Öjebyn farm.

systems. The field balance calculations are based on a production area of 45 ha in the organic system and 35 ha in the conventional, *e.g.* pasture excluded. All crops except potato are used on-farm for cattle feed. The stocking rate is 0.9 (organic) and 1.1 (conventional) cows per ha and the milk production 8.6 (organic) and 9.3 (conventional) tonnes of milk per cow and year on average (1997-2000). The farm and its management practices are described in more detail by Gustafson *et al.* (2003) and in Papers I and II.

The experimental design ('The Öjebyn project')

A soil survey was conducted in 1988, forming a basis for the split of the farm fields into two units with similar soil type distribution, enabling a full-scale comparison between organic and conventional production. The two systems have been managed by the same staff in order to enable comparability. The staff have also together with the scientists been involved in data monitoring and sampling.

The management plan for the organic and conventional farming systems included the same number of cows and about the same production volume of the crops. Hence, more agricultural land was allocated to the organic system since a decrease of about 20% in harvested yield was expected as well as a greater requirement for N from leguminous crops. This estimation was proven to be reasonably accurate (Jonsson, 2004). The main differences in management practice between the two systems are: (1) No mineral fertilisers and pesticides are used in the organic system; (2) the organic leys are sown with a seed mixture having a higher percentage of clover; and (3) a feed ration low in concentrate (protein and mineral feeds) is used in the organic system where there is also *ad lib* availability of roughage. The self-sufficiency in feed (biomass) was 70% and 51% for the organic and conventional systems, respectively (Gustafson *et al.*, 2003). A lower self supporting level of fodder leads to a larger import of feed and may also lead to higher nutrient surpluses.

Soil characteristics

The farm includes a considerable diversity in soil types. In Paper III three soil types were identified, Eutric Regosols, Thionic Gleysols and Dystric Cambisols (according to the WRB system) (FAO, 1998) (Table 2 in Paper III). The Eutric Regosol is a homogeneous non-acid soil characterised by its high content of silt and fine sand (silt loam). The Thionic Gleysol has a similar material in the topsoil (non-acid loamy sand), overlying the acidic subsurface horizons developed in more clay-rich (up to 25% clay) and sulphidic sediments ('acid sulphate soil'). The Dystric Cambisol has 20% clay content in the whole soil profile and a fairly low pH. Acid sulphate soils are common in the coastal area of the Bay of Bothnia. The low pH in these soils is caused by oxidation of iron sulphides due to aeration associated with isostatic land uplift and the fields being systematically drained with open ditches and/or tile drains (Öborn, 1994). The low pH can lead to increased mobilisation of metals and enhanced leaching has been observed in acid sulphate soil areas (Andersson *et al.*, 1988; Åström, 2001). Globally, there are a total of approx. 24 million hectares where acid sulphate soils and potential acid sulphate soils are a dominant feature of the landscape (ISRIC, 2004). These soils are mostly located in south-east Asia, west Africa and along the north-eastern coast of South America. However, acid sulphate soils occur locally in many countries, and in Sweden they cover about 140 000 ha and constitute about 5% of the arable land (Öborn, 1994).

Balance calculation

In Papers I to IV, element field balances were calculated for the Öjebyn farm. These field balances were calculated both as average field balances (average for all crops included in the crop rotation) and for individual crops. Figure 4 illustrates the different input and output flows included in the field balance calculation at Öjebyn farm. The diffuse flows (atmospheric deposition and losses by soil water) are also included. There is a large internal circulation of elements in farmyard manure, urine and feed crops.

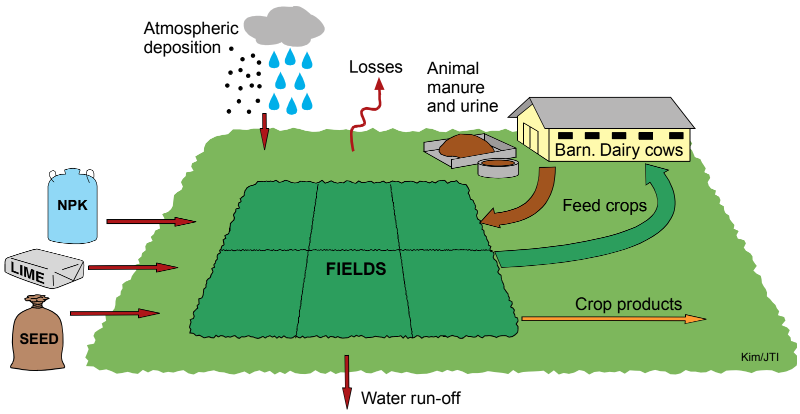

Figure 4. Schematic illustration of the field balance with the different inflows and outflows at the Öjebyn dairy farm. Input flows not included in the figure are via pesticides and N fixation.

In Paper IV, element farm-gate and barn balances were also calculated for the Öjebyn farm. The balance equations (Eq 2-4) used for the different scales were:

Farm-gate balance *= Purchased Products - Sold Products = (Purchased feed + Mineral fertilizers + Lime + Pesticides + Seeds + Heifers + Water + Sawdust (bedding material)) – (Milk + Potatoes + Cows for slaughter + Calves)* (Eq 2)

Barn balance *= Inflows to the barn - Outflows from the barn = (Feed (purchased and home-produced) + Heifers + Water + Bedding material (straw and sawdust)) – (Milk + Cows for slaughter+ Calves + Solid manure + Urine)* (Eq 3)

Field balance *= Inflows to the field - Outflows from the field = (Mineral fertilizer + Lime + Pesticides + Seeds + Solid manure + Urine + Atmospheric deposition + N-fixation) – (Harvested crops + Leaching + Surface run-off)* (Eq 4)

The water run-off from the field was divided into leaching and surface run-off. There was high surface runoff since the soil was frozen for about 6 months each year. The main part of the rooting zone was considered to be above the 50 cm soil depth and hence the leaching losses were defined as the element losses in water percolating from the rooting zone at 50 cm depth.

Data collection and chemical analyses

Element flows were estimated by multiplying the quantity (dry mass or volume of water) by their element concentrations. Table 1 describes how the different field flows were quantified. For three years (1997-1999) the different inflows and outflows at farm, barn and field level were sampled, analysed and quantified at the Öjebyn farm. More detailed descriptions of the quantification of the on-farm field flows are presented in Papers I-II. The quantification of the farm-gate and barn inflows and outflows are briefly presented in Paper IV. More detailed information on the sampling and analyses of the barn inflows and outflows are presented in Gustafson *et al*. (2003).

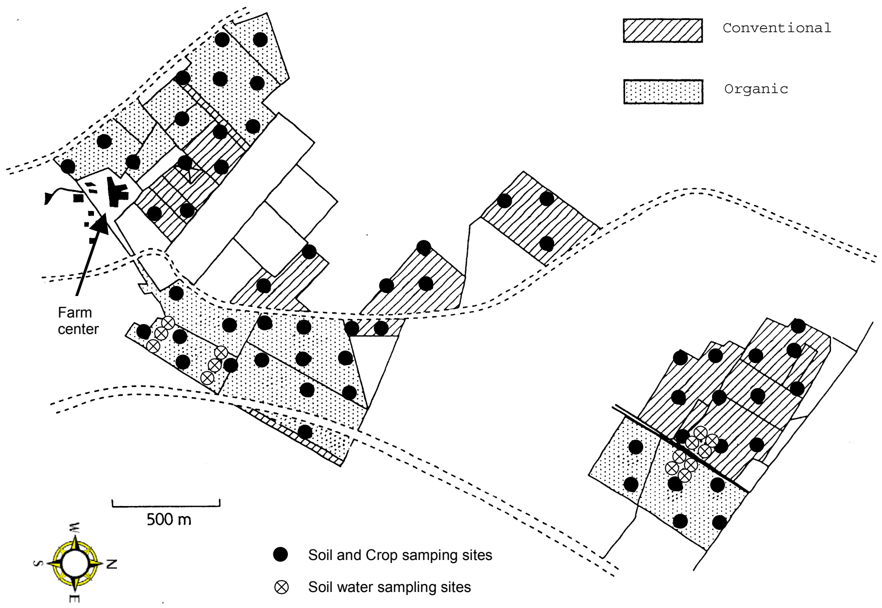

Figure 5. The distribution of sampling sites at the Öjebyn farm, 57 fixed GPS soil and crop sampling sites (9 sites on pasture) and the 14 soil water sampling sites.

Soil water samples were collected for five years (1998-2001) with suction cup lysimeters at four different field sites at the Öjebyn farm (Figure 5). The lysimeters were installed at the soil depths of 25, 50 and 80 cm with three or four

Table 1. *The methods for quantifying the different field flows and the lowest level of observation used in the statistical analyses. Element flows were estimated by multiplying the quantity (dry mass or volume of water) by their element concentrations*

Flow	Sampling years	Quantity		Concentration	
		Estimation/Sampling	Observation level	Estimation/Sampling	Observation level
Manure	3	Farm record on number of loads. Every fifth load weighed.	Farm	Sub-sample (1 L) taken from each load and bulked to give one composite sample per application event.	Field
Urine	3	Farm record on number of loads. Every tenth load weighed.	Farm	Sub-sample (2 L) taken from each load and bulked to give one composite sample per application event.	Field
Mineral Fertiliser	2	Farm record. Number of sacks	Farm	3 sub-samples taken from each sack and bulked to one composite sample per year and mineral fertiliser type.	Field
Deposition	IVL data[1] and literature[2]	Annual moss growth 116 g $m^{-2}yr^{-1}$	Regional	Concentration in the moss species *Pleurozium schreberi*, from 8 sites within 50 km of Öjebyn.[3]	Regional
Lime	3	Farm record	Farm	From distributor	National
Seed	3	Farm record	Farm	Analyses of farm crops	Farm
Harvested crop	3	Farm record. Each load weighed as it left the field.	Field	Sampled at 48 GPS fixed sampling points. Four sub-samples (total 1 m^2) per site. For potatoes, two metres of a row.	Field
Water run-off	5	Water balance calculation (Papers I-II). Hydrological SOIL model (Papers III-IV)	Field	Suction cup lysimeters at four sites and two depths. Sampling every second week during season.	Field

[1] IVL= Swedish Environmental Research Institute; [2] Rühling, Steinnes & Berg, 1996; [3] Relative efficiency factors 65, 41, 50% for Cd, Zn, Cu respectively. Baseline Zn and Cu concentrations in the moss tissue of 20 µg g^{-1} and 3.3 µg g^{-1}.

pseudo replicates for each depth (Paper III). Soil water chemistry at 20 cm soil depth was used to represent the element concentrations in surface water run-off. Water chemistry at 50 cm soil depth was used for the quantification of leaching losses. In Papers I and II, the soil water concentrations used in the calculation of element flows were based on one and two years of averaged data from two field sites at the farm respectively. In Paper III, the soil water concentrations were based on five years of data from four field sites at the farm. In Papers I and II, the volume of total water flow was estimated from a water balance calculation using the average data on precipitation (1961-90) and evapotranspiration (1961-1987) at Luleå airport (SMHI, 2004), and then allocated into surface run-off and water percolation through the rooting zone according to Gustafson *et al*. (1984). In Paper III, a water and heat transport model, SOIL (Jansson, 1998), was used to calculate surface run-off and water flows between different soil layers (leaching).

A soil survey was conducted in 1997 at the Öjebyn farm including a total of 57 fixed sampling sites (identified by their GPS positions), which were evenly distributed across the 105 hectares of agricultural land (one sampling site for each two hectares) (Figure 5). At the same fixed sampling sites, crop samples were collected prior to harvest during three years. At each sampling site, soil samples were taken at three soil depths; 0-25, 25-55 and 55-85 cm. These depths represented the plough layer (0-25 cm), the main rooting zone (0-55 cm) and the drainage depth (tile drainage) at about 90 cm.

In Paper IV some data are presented from a study within the project that quantify the contribution to the soil-plant system from weathering of soil minerals (Holmqvist, 2001). Both laboratory experiments and mathematical quantify modelling were carried out. The supply of mineral nutrients via the mineral weathering were estimated with a version of the PROFILE model, redeveloped to operate on agricultural soils with high contents of clay minerals such as vermiculites and illites.

Statistical analyses

Sampled data were treated statistically by analysis of variance (ANOVA) using the SYSTAT statistical software programme. An ANOVA design for a one-factor (farming system) analysis was used for the data in Paper I, a three-factor (farming system, crop, year) analysis was used for the data in Paper II and a five-factor (soil type, depth, year, season, farming system) analysis was used for the data in Paper III. To examine differences in the means of element concentrations in the soil between farming systems and fields, the data are analysed in a two-factor analysis in this thesis. For the significant factors in the ANOVA analyses, a pair-wise comparison of means was made using Tukey's t-test. Statistical probabilities of $p<0.05$ were considered as significant.

The data collected and analysed had different resolution in observation level for the statistical analyses, namely farm level, field level and within-field level, as illustrated in Table 1. Concerning inflows (solid manure, urine, mineral fertiliser, atmospheric deposition) and outflows (harvested crops, leaching, surface run-off) the coefficients of variation (CV) ((standard deviation/mean value) x 100) were calculated from three or five years of data on quantities and concentrations in the different flows (Papers II and III).

Overview of the papers included in the thesis

The thesis is based on data collected from the Öjebyn experimental farm (Table 2). The management regimes, conventional and organic farming, was considered in all Papers. The benefit of the approach of using one case study farm was that the quantitative and qualitative relationships between manure-soil-crop-animals-manure could be studied within the same system. Only then is it possible to study the flows of elements and how they influence each other and the quality of feeds and foods that are produced. Data were collected at the farm for three seasons or more which is a better situation than the more common practice of one-year studies.

Table 2. *Basic description of the different papers in the thesis. All investigations were carried out at the Öjebyn farm in Northern Sweden. The elements in brackets were only partly included in the study*

Paper	Scale	Sampling year	Aim	Element
I	Field	1998	Quantify flows and balances.	K, Mg, P, Cd, Cu, Zn
II	Field	1997-1999	Annual variation in the quantified element flows and balances.	(N), K, Mg, P, Cd, Cu, Zn
III	Field	1998-2002	Leaching and surface run-off losses	Cd, Cu, Zn
IV	Farm-gate/ Barn/Field	1997-2000	System approach, combine scale	K, P, (Cd), Zn

The aim of Paper I was to quantify K, P, Mg, Cd, Cu and Zn flows and balances at field scale and to assess the degree of imbalance (Table 2). In Paper II the element flows and balances were calculated for three years (1997-1999) to determine the accuracy of the element balance in connection with temporal and spatial variability. In this Paper N was also included. In both Paper I and Paper II, the output flows via leaching and surface run-off were identified as one of the main output flows in the metal balance. To increase the accuracy of the trace metal balances the Cd, Cu and Zn water run-off (leaching and surface run-off) were quantified with higher precision in Paper III. In Paper IV the whole farm-scale aspect was addressed, and the field balances for K, P and Zn were complemented with farm-gate and barn balance calculations. A first attempt was also made to use the Farmflow model for P dynamics in two senarios.

Results and Discussion

Farm-gate and field balances in organic and conventional dairy farming at the Öjebyn farm

Farm-gate and barn balances were calculated for P, K and Zn and average field balances were established for P, K, N, Mg, Cd, Cu and Zn. The average field balances were calculated as an average for all crops included in a crop rotation. For those elements where farm-gate, barn and field balances were calculated the results showed that the flows in the farm gate balance were considerably smaller than the flows at field and barn level.

Phosphorus balances

The *farm-gate balance* showed that inflows to both systems were rather low, but higher in the conventional system than in the organic, where the difference between inflow and outflow of P was smaller. The farm-gate P balance for the conventional system was 2-5 kg ha^{-1} yr^{-1} while for the organic system it was –2-+0.5 kg ha^{-1} yr^{-1} (Figure 6). The largest inflows of P were associated with purchased feed, with a larger proportion in the conventional system. The outflow of P with milk in dairy production was considerable. The conventional system exported larger amounts of P with milk per hectare than the organic system. The conventional system was able to produce more milk per hectare, which meant a larger outflow of P via milk. The P average *field balance* was slightly positive in all years in both the organic (1-6 kg ha^{-1} yr^{-1}) and conventional (3-9 kg ha^{-1} yr^{-1}) system (Table 3a). The main inflow of P was in solid manure (85%) and the main outflow was in the harvested crops (~100%). The largest crop outflow was associated with ley and oats/pea. Low concentrations of P in water made losses by leaching from the farm small in comparison with the flows within the farm. The farm gate balance and the field balance indicated the same result, namely that P was approximately in balance or slightly positive in both the organic and conventional system.

Potassium balances

The *farm gate balance* showed a K surplus/deficit of 12-33 and -1- +4 kg ha^{-1} yr^{-1} for the conventional and organic system, respectively (Figure 6). The *barn balance* for K was positive, since an important proportion of the K inflows could not be found in the outflows (Paper IV). This indicated that unaccounted K losses occurred in the barn system. A potential pathway for K losses may be press water formed during ensiling. The field balance may confirm this observation by the fact that the K concentration in the harvested oats/pea and ley at the field was slightly higher (25-35 g kg dw^{-1}) than the K concentration in the silage in the barn (25 g kg dw^{-1}) (Gustafson *et al.*, 2003; Paper II). The largest inflow of K was with silage, followed by purchased feed. On a per hectare basis, the conventional system had a larger K inflow with silage and purchased feed than the organic system. The largest outflow of K was found in solid manure and urine, and the flow was larger in the conventional system than in the organic when related to the hectares used for production.

The average *field balance* for K (the range was -29 to -15 kg ha^{-1} yr^{-1}) indicates that K inflows were smaller than K outflows in all years in both systems except for 1998 in the conventional system (59 kg ha^{-1} yr^{-1}) (Table 3a). The positive K balance in 1998 was due to high amounts of urine spread on the conventional fields and a comparatively low harvest. The manure and urine accounted for the main K inflow (85%). The main outflow was accounted for by the harvested crops (K 95%) and the largest crop outflow was associated with ley and oats/pea. The K outflow in the harvested crops was larger in the conventional system than in the organic for all years. Fagerberg *et al.* (1996) also calculated nutrient field balances at Öjebyn farm during five years and achieved similar results to ours regarding K.

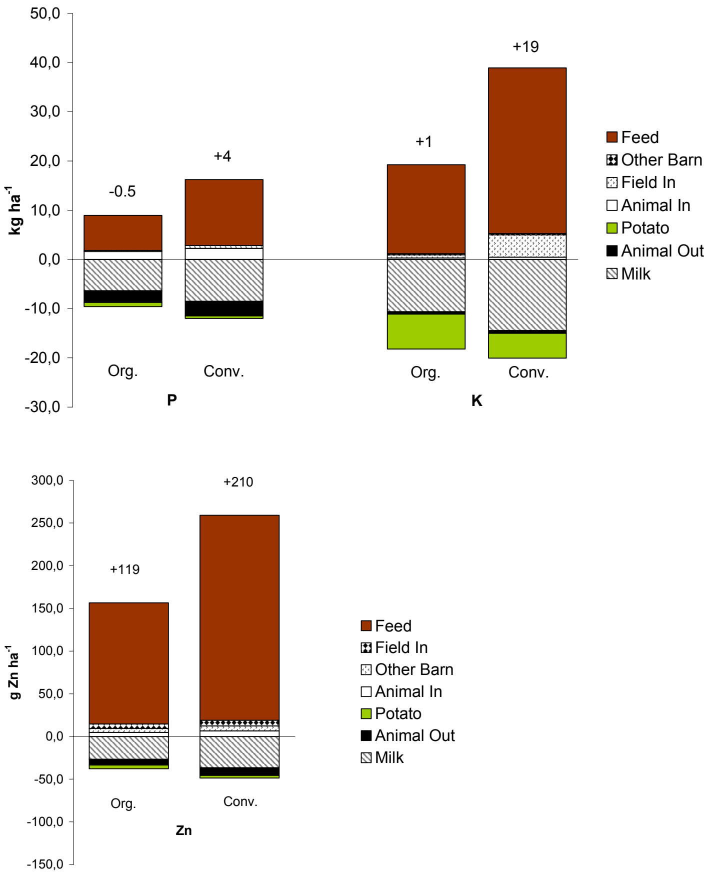

Figure 6. Farm gate balance for P, K and Zn in organic (Org) and conventional (Conv) dairy production. Annual averages calculated for three years of measurement based on the area used for production (ha^{-1} yr^{-1}). Other barn= sawdust, water; Field In= Mineral fertiliser, lime, pesticides; Animal In= Heifers; and Animal Out= Calves and cows for slaughter. The numbers above the bars show the resulting balances (inputs-outputs).

Table 3a. *Inputs and outputs of P, K, Mg and N (kg ha^{-1}yr^{-1}) for the arable fields in the organic (Org, 45 ha) and conventional (Conv, 35 ha) farming system, given as an average for the crops included in the crop rotation. The input and output flows in the different Papers were quantified for one, three or five years (1997-2001). In the case of more than one year, the flow or balance was first calculated for each year and then from that calculated as mean ±standard deviation, which is shown in this table.*

	Flow	**Year**	**K**		**P**		**Mg**		**N[2]**		**Paper**
			Org	Conv	Org	Conv	Org	Conv	Org	Conv	
Input	Solid manure	98	63	73	15	19	12	16			I[1]
		97-99	62±4	66±7	17±2	20±3	13±1	16±3	69	72	II
	Urine	98	39	99	0.2	0.3	1	3			I
		97-99	47±12	81±16	0.4±0.5	0.3±0.2	1±1	2±1	29	37	II
	Mineral fertilizer	98	-	5	-	2	-	6			I[1]
		97-99	-	5±5	-	1±1	-	4±2	-	33	II
	Lime	98	0	0	0	0	41	91			I
		97-99	0	0	0	0	29±25	30±53	0	-	II
	Seed	98	17	22	4	3	2	1			I
		97-99	16±1	18±4	3±1	3±1	1-2	1	10	10	II
	Deposition		1	1	-	-	-	-	2	2	I
Output	Harvest	98	123	136	16	15	11	9			I
		97-99	138±19	159±22	17±2	17±2	12±1	11±2	128	148	I[1]
	Leaching	97-99	3	3	0.0	0.0	8	8	16	16	II
		98-01	-	-	-	-	-	-			-
	Surface run-off	97-99	2	2	0.1	0.1	17	17	3	3	II
		98-01	-	-	-	-	-	-			-
Balance		98	-8	59	3	9	20	83	-	-	I
(In-Out)		97-99	-17±8	7±46	3±3	7±3	7±25	17±58	9	7	II
		98-01	-	-	-	-	-	-	-	-	-

[1]The element flows for the potato crop from Paper I have been recalculated to facilitate a comparison between Papers I and II. [2]The N balance eq. includes input via N fixation in the ley (46 kg ha^{-1} year^{-1} in the organic system and 20 kg ha^{-1} year^{-1} in the conventional).

Table 3b. *Inputs and outputs of Cd, Cu, Zn (g $ha^{-1}yr^{-1}$) for the arable fields in the organic (Org, 45 ha) and conventional (Conv, 35 ha) farming system, given as an average for the crops included in the crop rotation. The input and output flows in different papers were quantified for one, three or five years (1997-2001). In the case of more than one year, the flow or balance was first calculated for each year and then from that calculated as mean ±standard deviation, which is shown in this table.*

	Flow	**Year**	**Cd**		**Cu**		**Zn^2**		**Paper**
			Org	Conv	Org	Conv	Org	Conv	
Input	Solid manure	98	0.38	0.47	46	64	344	487	I[1]
		97-99	0.38±0.09	0.51±0.20	52±5	66±3	355±32	474±18	II
	Urine	98	0.01	0.01	7	16	18	42	I
		97-99	0.01±0.01	0.03±0.02	7±4	17±11	17±3	55±20	II
	Mineral fertiliser	98	-	0.01	-	15	-	8	I[1]
		97-99	-	0.003±0.01	-	7±8	-	3±4	II
	Lime	98	0.06	0.14	0	0	2	5	I
		97-99	0.05±0.04	0.05±0.08	0	0	3±4	2±3	II
	Seed	98	0.02	0.04	7	7	35	23	I
		97-99	0.02±0	0.03±0.01	6±1	6±1	26±8	21±2	II
	Deposition		0.34	0.34	3	3	82	82	I
Output	Harvest	98	0.12	0.16	40	36	141	145	I[1]
		97-99	0.18±0.05	0.17±0.04	38±3	40±5	159±21	160±14	II
	Leaching	97-99	0.10	0.10	21	21	12	12	II
		98-01	0.22±0.20	0.22±0.20	50±33	50±33	24±20	24±20	III
	Surface run-off	97-99	0.17	0.17	57	57	17	17	II
		98-01	0.13±0.09	0.13±0.09	43±18	43±18	16±9	16±9	III
Balance		98	0.42	0.58	-55	-9	311	482	I
(In-Out)		97-99	0.35±0.08	0.52±0.24	-48±8	-19±13	295±47	452±45	II
		98-01	0.28±0.22	0.45±0.22	-65±48	-43±48	255±27	405±27	III

[1]The element flows for the potato crop from Paper I have been recalculated to facilitate a comparison between Papers I and II. [2]The Zn balance eq. includes input via pesticides (9 g ha^{-1} $year^{-1}$ in the conventional system year 1998).

Nitrogen balances

In the conventional crop rotation, the N application was based on the N requirements of the crops according to nutrient supply recommendations for Northern Sweden (Alskog, 1999). The mineral fertiliser application rate in the conventional system was adjusted according to manure and urine application and clover content in the ley. From this perspective the main focus in the fertiliser management practice was to balance the N requirements of the crops. However at this northern location (>65°N) temperature is a limiting factor for production and fertiliser application rates are therefore rather low, leading to low surpluses.

Öborn (2004) reported N *farm-gate balances* for Öjebyn that showed a surplus of 143 kg ha^{-1} in the conventional system and 25 kg ha^{-1} in the organic. The average *field balance* for N was slightly positive in both the organic (9 kg ha^{-1} yr^{-1}) and conventional (7 kg ha^{-1} yr^{-1}) system (Table 3a). Flows unaccounted for in the N balance calculation were the diffuse flows, denitrification, and ammonia emissions. The positive balance can be assumed to be associated with these flows. Fagerberg *et al*. (1996) reported a large temporal variation in calculated N field balances (approximately -20 to 70 kg N ha^{-1}) at the Öjebyn farm.

Magnesium balances

The average *field balance* for Mg was positive in all years when lime (Dolomitic limestone) was applied due to 70% of the Mg inflow derived from the liming in those years (Table 3a). The organic fertiliser input and the removal with the crop balanced each other in all years. The Mg balance was negative in years with no lime application due to the outflow via water run-off.

Zinc, cadmium and copper balances

The Zn *farm gate balance* as well as the *field balance* for Cd and Zn indicated that the inflows of Cd and Zn exceeded the outflows, resulting in risks for soil accumulation. For Zn, the surplus in the farm gate balance was twice as high in the conventional (149-255 kg ha^{-1} yr^{-1}) as in the organic (97-131 kg ha^{-1} yr^{-1}) system (Figure 6). The main inflow in the farm gate balance was via the purchased feed and the main outflow was via the milk. The average *field balances* for Zn were positive in all years in both the organic (330-390 kg ha^{-1} yr^{-1}) and conventional (450-490 kg ha^{-1} yr^{-1}) system (Table 3b). The main inflow of Zn in the field balances was manure (75% Zn). The main outflow of Zn was accounted for by the harvested crops (75%), ley and forage crop (oats/pea) being the major contributors. The *barn balances* for Zn were negative, outflows>inflows, strongly indicating an inflow from some Zn source in the barn and/or manure handling system. This has also been reported in other studies (Moolenaar & Lexmond, 1998; De Belie *et al.*, 2000).

In the average *field balance* for Cd, fertiliser applications and crop removals represented a smaller proportion of the total inflows and outflows, while atmospheric deposition (40%) and leaching/surface run-off (70%) were larger (Table 3b). The field balances indicated that the Cd balances were positive in all years both in the organic (0.27-0.42 g ha^{-1} yr^{-1}) and conventional systems (0.26-0.72 g ha^{-1} yr^{-1}).

The Cu *field balances* were negative in all years in both farming systems, mainly due to the large outflow via leaching and surface run-off (Table 3b). Furthermore, for Cu the main inflow was via the organic and mineral fertiliser application (85%) but the distribution between the outflows was about equal between removals in harvested crop and leaching.

The general trends for all trace metals studied were that the farm-gate and average field balances were more positive (Cd and Zn) or less negative (Cu) in the conventional farming system than in the organic for all years. This was mainly due to the inflows via the feed for each year being larger in the conventional farming system than in the organic and the animal manure being spread on a smaller area in the former system.

The Zn flows in the farm gate balances showed a smaller accumulation at the farm level than the field level. This is probably due to internal inflows to the system from *e.g.* concrete and metal equipment in the barn.

Element imbalances due to on-farm management practices

Consequences of farm management practices/decisions for element cycling could be identified in the calculated element field balances. Large variations in the element flows depending on whether the balance was calculated as an average for the whole crop rotation or for individual crops were also discovered. Some differences between the two farming systems, organic and conventional farming, could be identified.

Variation within the crop rotation

The element flows and field balances for individual crops differed considerably from the average balance for the crop rotation (Figure 7). This aspect of variation between crops in balance calculations within a crop rotation has been reported in other studies (Bacon *et al*., 1990; Van Beek *et al*., 2003; Saporito & Lanyon, 2004). The differences in nutrient balances between crops could be explained by differences in manure application and crop yields. A large within-farm variation between fields was observed for the manure application. The general pattern was that the largest manure inputs were associated with oats/peas, barley and potato crop, and consequently there was a tendency for positive balances in fields with these crops and negative balances for fields with ley. The imbalance in nutrient inflows/outflows between crops was strengthened by the fact that the ley crop that had the highest nutrient removal (most pronounced for K) did not receive any solid manure. Farmyard manure was not spread on the ley crop, for practical and/or hygienic reasons.

The element imbalances in the crop rotation are of great concern from a nutrient management perspective. For easily soluble elements like K, balancing the flows each year is important, considering that surpluses create the potential for luxurious consumption of K by the ley grass or leaching losses (Whitehead, 2000). In terms of K management, it may be important to reduce the amount of manure applied in single application events. Instead, there could be an increase in the frequency of application in the rotation or application to different crops within the rotation. For metals the main concern is long-term accumulation or depletion (for micronutrients). The situation with positive metal balances in certain years in the crop rotation (Figure 4 in Paper I) could potentially lead to larger metal leaching from those fields. However, higher metal concentrations in the soil water in those years could not be detected (Paper III).

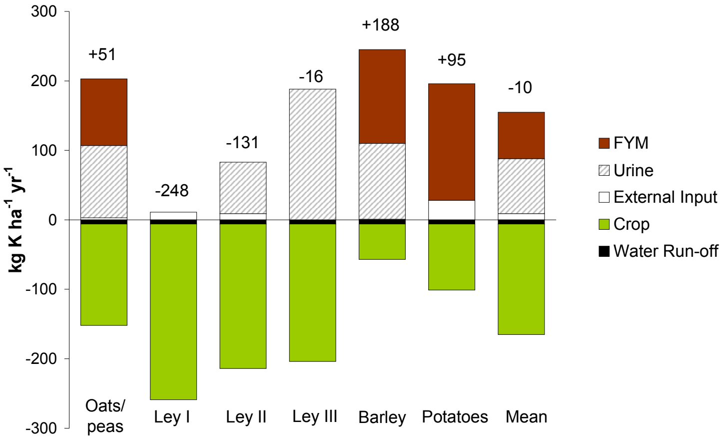

Figure 7. Potassium field balances (kg ha^{-1} yr^{-1}) for the different crops included in the crop rotation for the conventional farming system (average for three years). The water flow is an average value for the different crops. The number above the bar is the inflow-outflow balance. FYM= farmyard manure. External inflow= mineral fertilisers, lime, seed. (Paper IV)

Lime application had a large impact on the Mg balance and partly on the Cd balance. The inflow via lime took place only once in the crop rotation. For the elements Mg and Cd, this one time application should be considered in a field balance calculation for another year.

Both the grain and the straw were included in the balance calculation for barley (when the straw was harvested) (Table 3a and 3b). There are different element concentrations in the grain compared to the straw. There were significantly higher K and Cd concentrations in straw compared to grain. Furthermore, there were significantly higher Cu and Zn concentrations in grain compared to straw. Therefore, whether the straw was harvested or returned to the soil as an organic residue affected the K and metal balances for the barley crop.

In Table 3 the balance is calculated as an average for all crops in the crop rotation for three years. To improve the accuracy of the element balances and enable more detailed nutrient management plans, the element flows and their variation should be considered for individual crops.

Organic and conventional farming

The nutrient balance approach has been used in several studies to compare nutrient flows in organic and conventional farming systems (Nguyen, Haynes & Goh, 1995; Fagerberg, Salomon & Jonsson, 1996; Løes & Øgaard, 1997; Goulding *et al*., 2000). Watson & Stockdale (1999) identified the potential of field balance studies for predicting the impact of changing farming practices on nutrient use and nutrient management, *e.g*. conversion to organic management.

For immobile elements like P, farm-gate and field balances could be compared to check the accuracy of the balance calculation. The slightly positive P balance at farm-gate could be identified as an accumulation in the soil since the field balances was slightly positive (Figure 6; Table 3a). For P the farm-gate balance was mainly influenced by inflow with purchased feed and outflow with milk. The P balance was more positive in the conventional system compared to the organic and this could be explained by the higher degree of self-sufficiency of feed in the organic system. Organic farming aims at a high degree of self-sufficiency in feed (Stockdale *et al*., 2001).

Generally, at the Öjebyn farm, the element imbalances of most concern at field level were, the negative K balances and positive Cd and Zn balances (Table 3a and 3b). As a result of different management practices and different stocking rates, the K balances were more negative and the Cd and Zn balances were less positive in the organic system compared to the conventional one.

For N, P, K and Zn, the harvested crop was the main outflow in the field balance and the largest crop outflow was associated with ley and oats/pea. The K outflow in the harvested crops was larger in the conventional system than in the organic for all years. The K concentration in the conventional ley (33 g K kg dw^{-1}) was significantly higher than in the organic ley (26 g K kg dw^{-1}) (Paper II). This could be due to a higher proportion of clover in the organic ley (30% versus 15%), as clover generally has a lower K concentration than grass species (Whitehead, 2000), and/or to lower availability of K for crop supply in the organic system. There were larger inflows of K in urine and solid manure per hectare to the conventional fields compared to the organic fields, which most likely led to a higher crop uptake. In addition, mineral K fertiliser was applied in some years. Askegaard & Eriksen (2000) found that the K concentration of most crops in an organic dairy crop rotation was 20-40% lower than the conventional standard values often used in balance calculations.

In the field balances, the inflows of Cd, Cu and Zn via solid manure were larger in the conventional system than in the organic. There was a trend for the Cd, Cu and Zn concentration in the manure to be higher in the conventional system than in the organic (Paper II). However because of large variation within years, few samples and unbalanced sampling within each system, no significant difference were indicated in the statistical analysis. The trend for higher trace element concentrations in the conventional manure can also be seen in the calculated manure flow in all years. The Zn concentration in the conventional urine was significantly higher than that in the urine from the organic system (Paper II), which also could be seen in the calculated Zn flow for urine. One explanation to the difference in metal concentrations in the solid manure and urine between the systems could be due to the larger use of purchased feed, including mineral feed additives in the conventional system. This difference between systems in the solid manure and urine flow was also explained by higher application rates per hectare due to the higher stocking rate in the conventional system. Van Driel & Smilde (1990) concluded that on a farm with a high fraction of purchased feeds compared to home-produced feeds, there is a risk that metals will accumulate in the soil or leach to drainage water. A balance study in a more intensive production system, at a dairy farm in the Netherlands, showed Cd, Cu and Zn concentrations in manure (0.37, 33.2 and 167 mg kg^{-1} dw) that were considerably higher than at Öjebyn (Moolenaar & Lexmond, 1998). These authors found that the crop rotation and the choice of fertilisers clearly influenced the trace-metal balance of arable farming systems and that the role of feed management was very important.

The higher inflow of trace metals to the conventional fields via manure could not be detected in higher metal concentrations in the conventional crops compared to the organic crops (Paper II). One exception was the conventional ley III, which had significantly higher Cd, Cu and Zn concentrations than the organic ley III. This could be due to larger decrease in clover content from first- to third-year ley in the organic system (from 35% to 26%) (Jonsson, 2004). In the conventional system, there were no differences in clover content between first- and third-year leys (approximately 20%). Sauchelli (1969) reported large variation in Zn content among crop species, with legumes and other herbs having a higher concentration than cereals and other grasses.

Olsson *et al*. (2001) investigated the Cd concentration in dairy cows and animal products in organic and conventional production at the Öjebyn farm. Milk samples were taken regularly and the cows sold for slaughter were sampled in the slaughterhouse. The results showed that Cd concentrations were significantly lower in kidney, liver and mammary tissue from organically produced dairy cows. No significant difference could be detected in muscle tissue, while the Cd concentrations in milk were below the detection limit. The lower proportion of purchased concentrate in the organic system was the most probable explanation for the lower Cd burden (Olsson *et al*., 2001), since there were small differences in the Cd concentration of the home-produced feed crops.

Sustainability aspects of on-farm management practices

The main imbalances found in the element balance calculations in both systems were negative K balances and positive Cd and Zn balances (Table 3a and 3b). These tendencies were observed already after one year but were supported by results from the 3-year study (Paper II).

Weathering

The negative K field balances raise the question of whether K release by mineral weathering can contribute to crop supply or whether the current management practices are leading to depletion of the plant-available or potential plant-available soil pool of K. Previous calculations of K weathering rates in northern European agricultural soils (0-0.4 m soil depth) indicated a potential release rate from 3 (sandy loam) to 82 kg K ha^{-1} yr^{-1} (clay-rich soil and high soil-moisture content) (Holmqvist *et al.*, 2003), which can be compared with 12-14 kg K ha^{-1} yr^{-1} (0-0.75 m depth) for the silty loam soils at Öjebyn (Paper IV). These results indicate that the negative K field balances (Table 3a; Figure 7) could only partly be compensated for by K release from mineral weathering. For the organic system the average K concentration in the ley crop (23-36 g kg dw^{-1}, Paper II) was close to but not within the range for deficiency (12-16 g kg dw^{-1} (temperate grasses) and 10-23% g kg dw^{-1} (white clover)) (Whitehead, 2000). Considering individual crop samples, some were in the range of deficiency. Many soils have the capacity for sustainable supply of K even when there is net K removal. However, on sandy soils additional K inputs may be necessary in a more sustainable farming system. The reason is that forage crops have high demand for K, while sandy soils have low capacity to deliver K (Salomon, 1999).

Soil pool changes

The element field balance provides useful information on accumulation/depletion and thereby indicates potential problems in the future. One way to illustrate the sustainability is to relate the flows and balances to the existing nutrient or metal pool in the soil, and to assess the accumulation/depletion rate (mass per time and soil mass). The magnitude of this element change in the soil pool can then be related to changes in soil fertility, or the potential risk for losses or nutrient deficiencies. In this way the impact on the farm's natural basis for production, the soil, and the impact on the environment can be evaluated.

Trace metal accumulation in the soil may have negative environmental effects if the content increases above a certain critical concentration which can induce negative effects on soil biota and hence on the microbial and faunal activity. Soil microorganisms are far more sensitive to trace metal stress than soil animals or plants (Giller *et al.*, 1998). Therefore, prevention of trace metal accumulation in the soil is one of the prerequisites for sustainable agricultural production (Witter, 1996). There are no legal limit values on accumulation rates or critical loads in Sweden but the long-term goal of the Swedish Environmental Protection Agency is to ensure that there is no net accumulation of trace metals in agricultural soils (Notter, 1993).

The flow of elements into and out of an agroecosystem is generally a small fraction of the total stock of nutrients within the system. The magnitude of the positive metal balances and negative K balance at Öjebyn were compared to the existing soil pool (Table 4). Andersson (1992) calculated the annual trace metal change in Swedish agricultural soils (0-20 cm) during the 20th Century and found that for a crop rotation in the northern agricultural district, the calculated change in the topsoil was 0.26, 0.12, and 0.23% per year for Cd, Cu and Zn respectively. Compared to those values, the annual changes in the soil pool at the Öjebyn farm are presently lower for Cd in both farming systems. For Zn the annual change in the soil pool was lower in the organic system but the same in the conventional system (Table 4). However, Andersson (1992) may underestimate accumulation rates since he used leaching data from neutral arable soils (water sampled in the tile drainage system at 0.9-1.0), where metal concentrations were considerably lower than in the acid soils at Öjebyn.

Table 4. *P, K, Cd and Zn soil concentration, soil pool, balance between input and output and annual change in pool size in organic (Org) and conventional (Conv) farming system*

	System	Soil Depth	Element					
			P		K		Cd	Zn
			AL	HCl	AL	HCl	HNO_3	HNO_3
Soil concentration ($mg\ kg^{-1}$)[1]	Org	0-25	0.93	11.1	1.0	15.0	0.13	44
	Conv	0-25	1.1	10.3	0.76	23.9	0.05	43
	Org	25-55	0.47	9.7	0.72	26.1	0.10	36
	Conv	25-55	0.44	7.7	0.59	20.3	0.03	31
Soil pool ($kg\ ha^{-1}$)	Org	0-55	436	6980	551	14279	0.56	283
	Conv	0-55	454	5293	424	13299	0.35	206
Balance (kg or $g\ ha^{-1}$)[2]	Org	0-55	3	3	-17	-17	+0.35	+295
	Conv	0-55	9	9	7	7	+0.52	+449
% change[3]	Org	0-55	+0.69	+0.04	-3.1	-0.12	+0.06	+0.10
	Conv	0-55	+2	+0.17	+1.7	+0.05	+0.15	+0.22

[1] Ammonium lactate/acetic acid (AL)-extractable and 2M HCl-extractable (P and K), 7M HNO_3-extractable (Cd and Zn).
[2] $kg\ ha^{-1}$ (P, K) and $g\ ha^{-1}$ (Cd, Zn).
[3] Annual change in soil pool calculated as difference (balance)/soil pool (0-55 cm)*100. Balance according to the three-year average in Tables 3a and 3b.

Cederberg (2002) calculated the P surplus in one organic (+1 kg P ha^{-1}) and one conventional (+10 kg P ha^{-1}) dairy farm in Sweden. Related to the soil pool this gave in a 100 years perspective an increase in the P store in the soil by one tonne. She concluded that in a time-perspective longer than is usually discussed in agriculture (one or two crop rotations) the disparity can be substantial between livestock systems with different P accumulation in the soil.

Temporal and spatial variation in the different field flows - concentrations and quantities

The accuracy of an element field balance calculation can be improved if the uncertainty originating from temporal and spatial variation in the different flows is considered. As seen in Table 3a and 3b (years 1997-99) there was a wide range in some of the estimated element input and output flows measured in the three-year study. The variation/error range discussed in this section originates from both temporal and spatial variation. For the output flows, harvested crop and leaching, the spatial variation (differences between fields and/or soil types) could be captured from the within year variation between sampling points at different fields. The temporal variation as such could not be captured due to the fact that the crops within a crop rotation at the farm.

The variation in the flows depends on the variation in the mass flow of material (quantities) as well as on the element concentrations. Table 5 shows the calculated relative error (coefficient of variation) in the quantities and element concentrations of the different field inflows and outflows (data on harvested crops are given for the individual crops in the rotation).

Range of variation in the measured flows

Solid manure and Urine

For the solid manure flow in the organic system, the application rate had a similar variation as the element concentration. Cadmium was an exception, as the concentration varied more than the application rate. In the conventional system, the solid manure application rate varied less than the element concentration. Also in this case, the Cd concentration in the solid manure showed the largest variation. For the element concentration in solid manure, the variation between years was as large as between different sampling occasions within years (Paper II). This can partly be due to the heterogeneous nature of the manure and urine material, which makes it difficult to get representative samples. The sampling procedure used in this study was according to Rodhe & Jonsson (1998). They found that the element concentrations and DM content of solid manure were significantly different between loads on an individual farm. Their recommendation was that when sampling manually in connection with loading of a spreader, samples should be taken from all loads, including at least 10 sub-samples per bulk sample.

A recent Swedish survey compared the composition of manure and urine collected from organic and conventional dairy farms (Steineck *et al.*, 2000). When we compared this study with our results from Öjebyn it was possible to contrast 'within farm variation' with 'between farm variation'. It was found that the variation between years for the Cd and Mg concentrations in the manure at the Öjebyn farm was within the range of variation between farms in the Swedish survey (Steineck *et al.*, 2000). For all the other elements, the mean value and variation at the Öjebyn farm was lower than the range of variation found between farms in the survey. Moolenaar & Lexmond (1998) studied trace metal flows in different farming systems in the Netherlands. They also found that the trace metal concentration in the manure had a large variation and concluded that it is risky to use only estimates or literature values. On-farm monitoring is needed to enable reliable on-site quantification.

Table 5. *Total variation (coefficient of variation (CV, %)) in the quantity (kg dw ha^{-1}) and element (P, K, Mg (g kg dw^{-1}), Cd, Cu and Zn (mg kg dw^{-1})) and dry matter (%) concentration in the main field inflows. The calculations are based on three years data. If significant difference between organic (Org) and conventional (Conv) systems,were found two values are given. n= number of observations per system*

Input flow	Quantity		Concentration		
	CV (%)	n	CV (%)	Element	n
Solid manure	4 (Conv)	3	45	Cd	12-13
	11 (Org)		10-15	K, P, Mg, N, Cu, Zn	
			9	DM	
Urine	15 (Conv)	3	130	P	10-16
	27 (Org)		80-100	Cd, Cu, Zn (Conv)	
			50	Cd, Cu, Zn (Org)	
			30	Mg	
			15-20	K, N	
			19; 29	DM (Org; Conv)	
Depo-sition	-	-	17-25	Cd, Cu, Zn	8

The urine application rate, and particularly the element concentrations in the urine, showed a large variation. However, the element concentrations in the urine varied as much between years as within years (Paper II). The P and metal concentration in the urine had the largest variation. The variation was probably not due to spatial variability in the urine pit as the urine was mixed before sampling, which should be enough for obtaining representative samples. The large variation in element content in the urine could be due to varying amounts of solid manure being mixed with the urine and/or the DM content varying due to the amount of water leaching from the uncovered manure pad and infiltrating into the urine pit (Gustafson *et al*., 2003).

The harvested crop

The harvested crop had a variation in the element concentration and harvested biomass that was similar to or larger than the variation in the manure and urine flow. For all crops the Cd concentration had the largest variation of the elements investigated. The variation in dry matter content was low (CV around 10%) for all crops except for potatoes (CV 40-50%, Table 5). The variation between years in the harvested crop could be due to weather conditions, the spatial variation (differences between fields) and any changes in management practices. Our study included three growing seasons with quite different weather conditions with respect to precipitation and temperature (Paper II). The spatial variation, reflected by the variation between sampling points during individual years, seems to be as large as the total variation (temporal and spatial together). This is exemplified with the ley crop in Table 7.

Table 6. *Total variation, (coefficient of variation (CV, %)), in the quantity (kg dw ha^{-1}) and element (P, K, Mg (g kg dw^{-1}), Cd, Cu and Zn (mg kg dw^{-1})) and dry matter (%) concentration in the main field* *<u>outflows</u>*. *The calculations are based on three (crop) or five (water) years of data for both farming systems. If significant difference between organic (Org) and conventional (Conv) systems, two values are given. n= number of observations per system*

Output flow	Quantity		Concentration		
	CV (%)	n	CV (%)	Element	n
Oats/Pea	17	8	107; 52	Cd (Org; Conv)	13-17
			20-35	P, K, Mg, Cu, Zn	
			8	N	
Ley	15	26	52	Cd	35-42
			30	Mg	
			~20	K, N, Cu, Zn	
			10	P	
Barley (grain)	20	8	70; 40	Cd (Org; Conv)	10-13
			10-25	K, P, Mg, Cu, Zn	
			5	N	
Potato	10	7	45	Cd	4-8
			33	Cu	
			10-20	K, Mg, Zn, P	
			40; 55	DM (Org; Conv)	
Leaching[1]	60	14	68; 36; 58	Cd; Cu; Zn	15
Surface run-off[1]	35	15	55; 49; 60	Cd; Cu; Zn	15

[1] Variation calculated based on average annual values for five years and three soils.

Table 7. *Within year variation, spatial variation, (coefficient of variation (CV, %)), in the element (P, K, Mg (g kg dw^{-1}), Cd, Cu and Zn (mg kg dw^{-1})) concentration in the ley crop. The data are calculated for three years. Number of observations per year was 25-26*

Output flow	Concentration			
	Element	CV (%)		
		1997	1998	1999
Ley	Cd	48	36	55
	Cu	18	12	22
	Zn	14	15	25
	N	21	-	-
	P	9	11	13
	K	18	20	23
	Mg	28	20	30

Regional surveys in Sweden have been reported for nutrient and trace element concentrations in barley (Eriksson *et al*., 2000) and potatoes (Sandberg, 2002). These studies could be compared with our results from the Öjebyn farm to contrast the 'within-farm variation' with the 'between-farm variation'. The variations in element concentrations in the barley crop at the Öjebyn farm were within the regional (Eriksson *et al*., 2000) range of variation for all elements, except for K that had a higher mean value and variation. The variation in element concentration in the potato crop at the Öjebyn farm was within the regional (Sandberg, 2002) range of variation for Mg, Cd and Zn. For K, P and Cu the mean concentrations in potato were higher at the Öjebyn farm compared to the regional data, but the variations were quite similar. No comparative data were available for the oats/pea forage crop and the grass/clover ley.

The diffuse flows

The diffuse flows often have the greatest magnitude in the trace metal balances and in the present study they were the flows estimated with the least precision. Atmospheric deposition was an important inflow in the trace element balances, mainly for mainly Cd and Zn. As shown in Table 1, deposition was quantified from the annual amounts accumulated in a moss species at 8 sites in the local area. The variation connected to the atmospheric deposition is probably mainly connected to the spatial variability. The variation in the analyzed element concentrations accounted for in this statistical analysis was probably a smaller part of the total uncertainty in the estimated flow. Many factors *e.g.* estimated moss growth and relative efficiency factors are probably related to large variations. There was a large variation in the metal water run-off, as shown in Paper III. The range of variation was large both between years and between soil types. However, the metal outflows were comparable with those in other similar studies referred to in Paper III. The aim of Paper III was to estimate the water run-off with higher precision than in Papers I and II, so as to increase the accuracy of the metal balances.

Concentration versus quantity

The uncertainties in mass flows, such as errors in yield and amount of applied fertiliser, and the element composition both seemed to be of importance for the total variation in the calculated field flows (Table 5). Generally the element concentrations had a similar or higher variation than the mass flow of material. For Cd, the variation in the concentration seemed to affect the calculated flow more than for the other elements. The results indicate that the variation in the element concentration affects the total variation in the calculated element balance as much as the mass flow of material. This was not expected at the start of this study.

Implication of the spatial variation in the crop and water run-off flows

It can be assumed that the output flows, crop uptake and leaching losses, to a large degree are affected by the site-specific soil characteristics. The calculated relative errors for the Cd concentrations in these flows were large (Table 6). The following two examples are intended to illustrate the influence from spatial variation on the outcome of the metal balance calculation.

Harvested crop flow

According to the metal balance calculation, there was a higher metal accumulation in the conventional farming system compared to the organic system. This was not indicated by the metal concentrations in the soil. Instead, the Cd and Zn concentrations in the topsoil were significantly higher in the soils of the organic

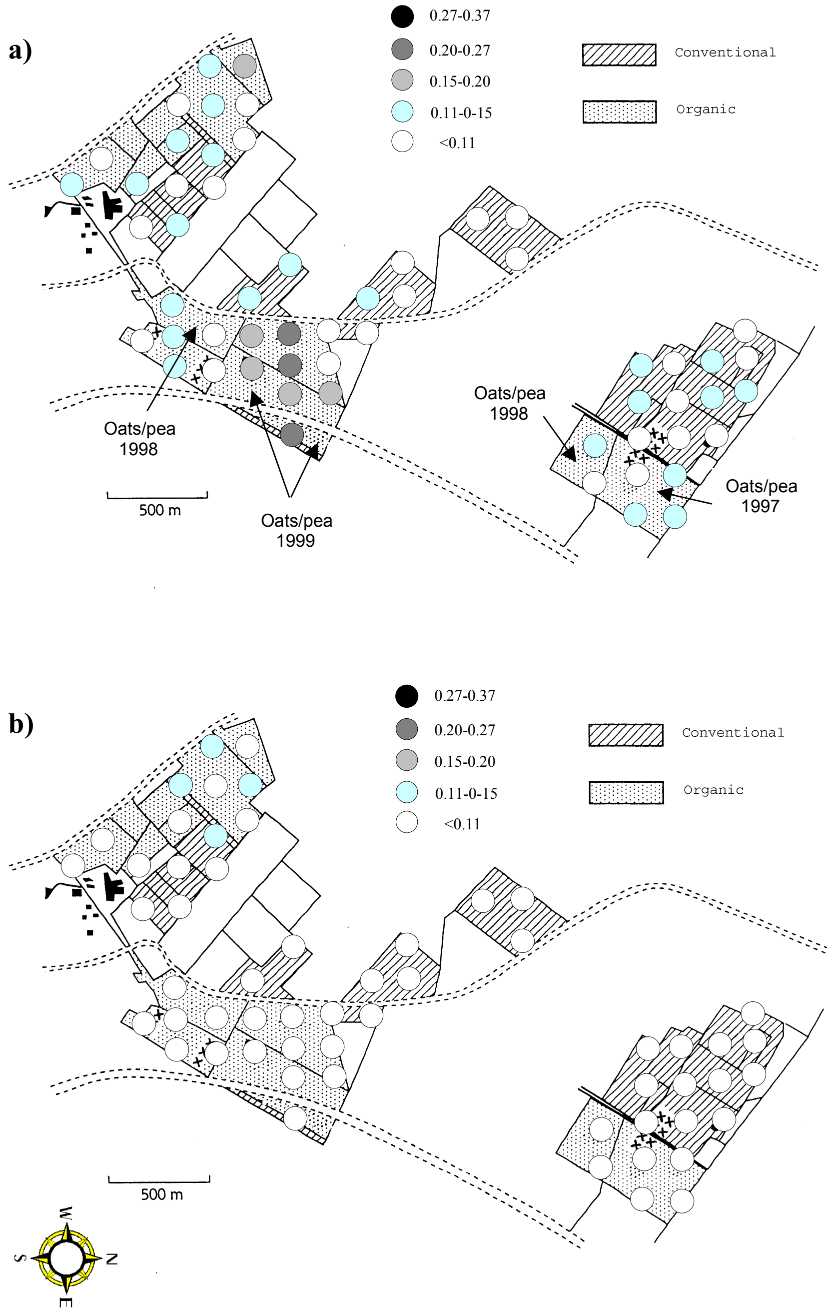

Figure 8. Soil Cd (mg kg^{-1}) concentration (HNO_3-extractable) at 20 cm (a) and 85 cm (b) soil depth 57 fixed sampling points evenly distributed across 105 hectares of agricultural land at the Öjebyn farm (one sampling point per two hectares). The fields that had oats/pea crop in 1997 to 1999 are indicated by arrows.

system compared to the conventional system (Table 4). Figure 8 shows the spatial variation of the Cd concentration in the topsoil and subsoil at the farm. There were three fields with organic farming that had clearly higher Cd concentration in the topsoil than the other fields. The Zn concentration was also higher in these fields. One explanation for the variation in metal content detected between fields could be historical management practices. In the 1980s, industrial lime (*kalkmesa*) was applied to these fields. The general conception is that this lime product was contaminated by trace metals (Simon Jonsson, pers. Comm.).

Plant bioavailability of trace metals varies with plant species (rooting depth, active mycorrhiza, root exudates *etc*), soil characteristics and trace metal loadings (Ross, 1994). The higher Cd and Zn soil concentrations (0-25 cm) in the organic fields could be detected in some crops. The oats and pea crop had significantly higher Cd and Zn concentrations in the organic system compared to the conventional system (Paper II). The spatial patterns of the Cd and Zn surface soil concentrations were also reflected in the oats/pea Cd and Zn concentrations. In the third of three sampling years, the Cd and Zn concentrations were very high in the oats/pea crop. In that year, the organic oats/pea crop was grown on two of the fields where industrial lime had been applied. The Cd and Zn concentrations were significantly higher in the crop grown on those fields compared to the same crop grown on other fields at the farm. The oats/pea crop seems to be a good 'indicator crop' of a higher metal content in the soil, probably because the vegetative part was harvested. Metal uptake in vegetative parts is usually more strongly correlated to soil factors than uptake in the grain/seed (Ross, 1994). The ley crop was not cultivated on those fields during the study period.

The higher Cd and Zn concentrations in the oats and pea crop yielded a significantly higher metal outflow via the harvested crop. Furthermore, this affected the metal balance calculation for the individual crop balance that year. The average Cd oats and pea outflow in the third year was 0.86 g ha^{-1} for the organic fields compared to 0.10 g ha^{-1} for the conventional fields. In a system comparison this spatial variation due to historical management practice will affect the outcome and has to be considered in the interpretation.

Water run-off flow

In Paper III it was shown that the metal concentration in the soil water collected in the subsoil varied significantly between soils. The parent material and chemical characteristics, such as pH, are important factors controlling metal solubility in soils (McLaren *et al.*, 2004). Eriksson *et al.* (1997) conducted a Swedish soil survey and found the average Cd, Cu and Zn concentrations in the topsoil (0-20 cm) to be 0.23, 14.6 and 59 mg kg^{-1} respectively. Compared to this, the average Cd and Zn concentrations in the soil at Öjebyn were lower, while the average Cu concentration was similar (Table 4; Paper III (Table 2)). However the subsoil at Öjebyn is locally very acid due to the occurrence of acid sulphate soils (Figure 9). A pH value lower than 4.3 in the subsoil was used for a rough identification of the acid sulphate soils. Based on the map in Figure 9, it was estimated that approximately half the area of the farm is situated on this soil type.

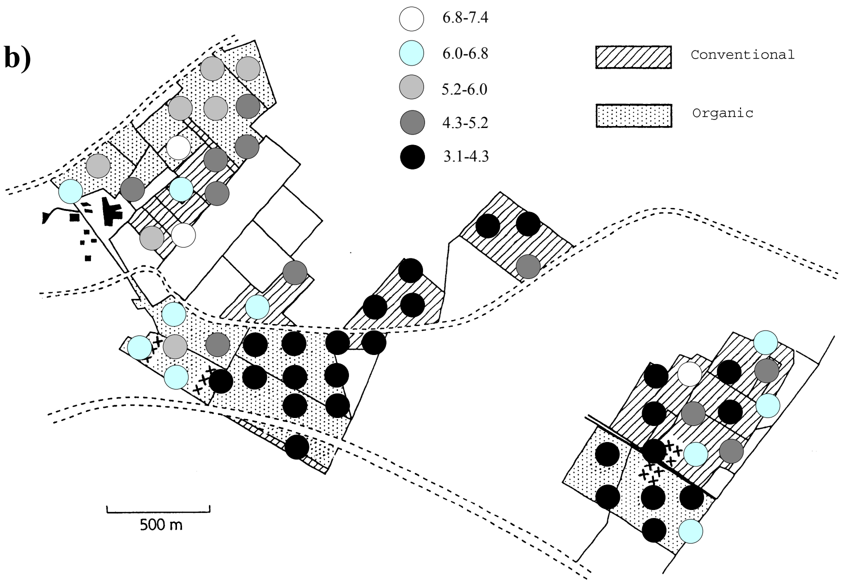

Figure 9. Soil pH- value at 20 cm (a) and 85 cm (b) soil depth at 57 fixed sampling points, evenly distributed across the 105 hectares of agricultural land at the Öjebyn farm (one sampling site per two hectares). Crosses indicate lysimeter sites where soil water was collected (Paper III).

The water run-off flows in the balance calculation in Table 3b is an average for the different soil types at the farm. However, the impact of different soil types on the Cd and Zn concentrations in the soil water was important. A Cd balance calculation for the 50 cm soil depth for the non-acid soil and the acid sulphate soil separately at Öjebyn showed a larger accumulation of Cd in the non-acid soil (+0.43 g $ha^{-1}yr^{-1}$) compared to the acid sulphate soil (+0.13 g $ha^{-1}yr^{-1}$) due to higher leaching in the acid soil (Paper III).

The role of the spatial variability, when Cd, Cu and Zn leaching were quantified, was the dominant aspect in Paper III. The lysimeters were only placed on a few sites on the farm. Thus when quantifying trace metal leaching for the farm we will have to extrapolate data from lysimeter site measurements to larger areas (farm). This has to be based on relationships between leaching/surface run-off and soil type (existing soil data). Thereby a scale translation 'upwards' can be made (Wagenet, 1998).

According to the metal balance calculation, there was a larger metal inflow in the conventional farming system via the higher fertiliser application compared to the organic system. However in our study there was no significant difference in metal concentrations in the soil water from the different farming systems. This implied that the differences in metal concentration in the soil water due to farming practices were of minor importance compared to variation between years and differences between soil types. This aspect has to be considered in a systems comparison of metal balance calculations.

Lessons learnt in relation to the interpretation of balance calculations

Farm-gate, barn and field element balances

Monitoring nutrient balances at both the farm gate and the field level can be a successful way of uncovering farm management concerns not obvious by determining nutrient balances at the farm gate alone. A combination of farm-gate, barn and field balances enables quantification of the internal flows and an identification of internal sinks and sources.

Individual crop versus crop rotation

The element flows and field balances for individual crops can differ considerably from an average balance for the crops included in a crop rotation. Differences are mainly due to management practices, but can also be due to site specific characteristics. In the average element balances for a whole farm, information can be lost which can lead to wrong interpretations of the balance. For detailed nutrient management planning, the balance should be calculated for each crop or each field. Saporito & Lanyon (2004) suggest that mapping the field balances at a farm may be useful to farmers because it will assist them in locating fields with extreme balances. The spatial dimension of farm activities can be highlighted by nutrient balance farm and field maps. These maps can be tools to assist producers and advisers in nutrient management planning and evaluation processes.

Several-year study versus one-year study

The between year variation in the calculated element balance can be large. Management practices and weather conditions are the dominating factors behind the annual variations affecting the element balance. The range in variation between years (the one-year balance versus the several-year balance) can most likely be so large that it influences the interpretation of the balance calculation. This indicates that balance calculations from one-year data can be very deceptive if they are interpreted in more general terms.

Standard data – farm-specific data

The accuracy of the field balance is lower than that of the farm-gate balance due to the fact that the field balance includes internal and diffuse flows that are more difficult to estimate than the flows related to purchased and sold products. One of the most important questions when trying to improve the accuracy and usefulness of element balances at different scales is how to quantify the internal flows, such as home-produced feed and manure/urine produced. Quantities of purchased feed are usually recorded, and the element concentrations in the feed can be declared by the seller. However, Mulier *et al*. (2003) point out that the accuracy of the data supplied by the feed or fertiliser industry could be improved. For certain products such as milk and meat, a standard chemical composition from the literature or statistics has to be used while for other products, especially home-produced feed (roughage) and manure, farm-specific analyses are very useful due to large variations and the fact that they constitute the main flows.

Site specific knowledge and system boundaries

If the element balance is to act as a useful tool, it has to be complemented with a good understanding/knowledge of the system studied. In field balances, the cultivated part (plough layer) of the soil is usually included within the systems boundary. However, the systems boundary could also include the main rooting depth since the rooting zone is an essential part of the agricultural production system. Moreover the farming activities and crop uptake change the quality of the soil, which in turn influences the output. The site-specific outflows, harvested crop and leaching losses, should be considered in this context. For example, it has been showed that in comparisons between farming systems with respect to element flows and balances, it is important that the local soil characteristics are considered to receive reliable results. There may be a way to reduce the error in the output flows by relating field flows to specific soil data (*e.g*. soil texture, parent material, chemical characteristics) and production systems.

The uncertainty of the element balance calculation depends to a large extent on the size and variation of the major flows. This implies that there will be a substantial error in the trace metal field balances if the outflows in surface water run-off and leaching are neglected. A good estimation of the trace metal leaching from agricultural soils makes it possible to get more accurate trace metal balances and thereby to use the balance calculation tool to assess the potential trace metal accumulation in soils and related sustainability aspects. Leaching losses of metals need to estimated for different regions and soil types based on field measurements and regional data on climate (water run-off) and parent material (soil texture and mineralogy), in combination with site-specific data on farm management practices (use of lime, fertilisers, *etc*.).

A fundamental issue in the delineation of system boundaries in space is to consider both the horizontal and vertical dimension. The choice of the lowermost boundary in the soil profile may have a very large effect on the final inflow-outflow metal balance. For example, in a non-acid soil at the Öjebyn farm, the metal balance calculated for the plough layer became less positive than the balance calculated for the main rooting zone (50 cm) due to higher leaching from the plough layer, while for a soil with an acid subsoil, the metal balance calculated for the drainage depth (90 cm) became less positive than for the root zone balance due to high leaching from the lower depth.

Conclusions and Recommendations

Monitoring nutrient balances at different scales (farm-gate, barn, field) proved to be a successful way of identifying farm management issues not revealed by determining nutrient balances at the farm-gate alone. The barn balances for Zn were negative, outflows>inflows, strongly indicating inflows from corrosion of metals in the barn system. The barn balance for K was positive for both systems, indicating that unaccounted-for K losses occurred. A potential pathway for K losses may be press water formed during ensiling.

At the Öjebyn farm, the element imbalances of most concern at field level were in both the organic and conventional farming systems the negative K balances and positive Cd and Zn balances. At field scale the K concentrations in the conventional ley crop were higher than in the organic ley leading to larger K outflow in the harvested crop. The trace element flow via manure was larger in the conventional system than in the organic system in all years, leading to more positive Cd and Zn field balances in the conventional system.

This study has shown that the error range in the estimated input and output field flows can introduce considerable uncertainty in the element balance calculation. In most cases the main sources of uncertainties were within the element concentrations as well as in the amounts of material. The spatial variation in the harvested crop flow and water run-off was as large as, or even larger than, the temporal variation. Large error ranges were associated with all on-farm quantified field flows, such as organic fertilisers, harvested crop and water run-off, but with the largest error in the output flows. Furthermore, the error within the field flows varied between elements. The trace metal balances were estimated with the least precision. The diffuse flow, water run-off, had the largest variation.

At the Öjebyn farm, the uncertainty due to spatial and temporal variation within the inflows and outflows affected the field balances to a larger degree than the difference between the farming systems. The study demonstrates that local soil characteristics have to be considered in comparisons between farming systems with respect to element flows and balances. The lower K concentration in the organic ley is most probably due to the current management system. However, it is not only the current farming system but also the soil-specific characteristic and historical management practices that are important. For example, at the Öjebyn farm site-specific characteristics such as low soil pH or high soil metal concentration affected the outflows through elevated water run-off flow and crop flow, respectively. Consequently, the soil type and historical management practices gave significant effects in the calculated element balance for Cd and Zn.

Some recommendation for the future use of element balances:

- Trace metal balances should be incorporated into available balance calculation tools. This could serve as a basis from which to develop policies to address environmental issues related to trace metals in agricultural systems.
- Field balance calculations within a farm are related to large imbalance due to different management practices for different crops. This indicates that for detailed nutrient management planning there is a need for field balances for individual fields and crops.
- The variation due to error in the balance calculation has to be recognised and could be a standard part of the element balance calculation procedure. Then guidelines have to be developed for including analyses of quantified error ranges and confidence limits for different element input and output flows. Data from this study can be a part of that development.
- For main flows and flows with large variation there is a need for farm-specific data rather than standard values. This is the case for home-produced feed (roughage) and manure in livestock production. For the water run-off flow improved regional data related to climate, soil type and management practice might be the way forward.

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