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Nutrient Use Efficiencies and Leaching of Organic and Conventional Cropping Systems in Sweden

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ABSTRACT

Organic farming has been proposed as a means of reducing leaching and improving the use efficiency of plant nutrients in agriculture. In such systems, nutrient inputs originate from various organic sources or from naturally occurring minerals with low solubility. In this study, measurements of leaching and crop uptake of N, P, and K and determinations of mineral N in soil were conducted in tile-drained plots during a 6-yr period in two organic crop rotations, one with and one without addition of animal manures. In the latter, N was provided by green manures. For comparison, two conventional systems in which mineral fertilizers and pesticides were used (one with cover crops) were also included. Leaching loads of N were smallest in the conventional system with cover crops, on average 25 kg N ha^{-1} yr^{-1} over the 6-yr period. The corresponding amounts in the other systems were 39 (organic with animal manure), 34 (organic without animal manure), and 38 (conventional) kg N ha^{-1}. Phosphorus-leaching loads were small overall in all systems (<0.25 kg ha^{-1} yr^{-1}). Potassium-leaching loads reached on average 27 kg ha^{-1} yr^{-1} over the 6 yr in the conventional systems and 16 kg ha^{-1} yr^{-1} in the organic systems. When N leaching was expressed as a percentage of total N removal during the 6-yr period (leaching plus harvested N with crops), it represented 59% in the organic system without animal manure, 33% in the conventional system, and 22% in the conventional system with cover crops. These results clearly suggest that N use efficiency is improved if inorganic N fertilizers are used rather than green manures, especially in combination with cover crops. The superior system from all considerations was the conventional system with a cover crop.

Efficient use of nutrients within agricultural production systems has been in focus for several decades. A major contributing reason for this is that negative effects on surface water and groundwater quality, which to a large extent are attributed to agricultural nonpoint-source pollution of nutrients, have been observed in many countries. The problem is recognized especially in cold and humid regions, where large amounts of water percolate through soil during periods without a crop (Morecroft et al., 2000). The interest in new methods for producing crops in an environmentally safe manner has therefore increased in recent years (Kirchmann et al., 2002). Among such new methods and changes in agricultural systems, the introduction of organic farming practices has been proposed on the presumption that such practices conserve essential nutrients and reduce the adverse impact of agriculture on water quality. This shift toward organic farming has received considerable political attention around the world. For example, the Swedish government has established the goal that by the year 2005, 20% of agricultural land should be under organic farming, even though there is a lack of sound scientific evidence to support such legislation (Trewavas, 2004). In 2004, this figure was about 13% when marginal grazing land, which is sometimes classified as organic land, was excluded. In organic cropping systems, soluble inorganic fertilizers are not allowed, although some soluble inorganic K fertilizers are permitted under restricted conditions. Nutrient inputs in such systems originate either from various organic sources (e.g., animal and green manures) or from naturally occurring minerals with very low solubility (e.g., apatite for P). Other features related to the use of nutrients in organic cropping systems include enhancement and improvement of the biological conditions for symbiotic N_2 fixation, emphasis on the recycling of animal manures, and creation of a balance between the number of animals and the cultivated area for crops (Kirchmann and Bergström, 2001).

For both organic manures and primary minerals to be efficient, they have to deliver soluble inorganic nutrients at a time when the crops need them. In cold humid regions, this typically coincides with rapid uptake of nutrients in spring/early summer. If the nutrients are released too late in the growing season or after the crop has been harvested, they can potentially leach through the unsaturated zone and contaminate groundwaters or, if captured by tile drains, surface waters. This is especially critical for N, which can cause large leaching loads in combination with the use of both animal and green manures (Bergström and Kirchmann, 1999, 2004). In contrast, other studies have shown that leaching of N does not increase in response to organic farming practices, and in some cases, it has even been shown that N leaching is lower in organic than in conventional farming systems (Goss and Goorahoo, 1995; Eltun and Fugleberg, 1996).

Besides being a potential contaminant causing eutrophication in freshwater bodies, P is also a limited resource, and both these aspects have to be considered in sustainable management of agricultural systems. In addition to P in organic amendments, organic farming relies on P from apatite, whereas more soluble inorganic P fertilizers are used in conventional agriculture. Phosphorus is taken up by crops in soluble inorganic form as phosphate anions (Leinweber et al., 2002). Therefore, adding apatite could cause a similar problem to adding organically bound N in manures in that the release of P

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Abbreviations: CCC, conventional with cover crops; CON, conventional; DM, dry matter; OAM, organic with animal manure; OGM, organic with green manure.

is too slow and often occurs at times when there is no crop uptake of P.

Potassium is neither a major source of contamination of natural waters nor a limited resource. However, under certain conditions, lack of sufficient K for crops can be a problem. For example, in organic cropping systems where the use of soluble inorganic K fertilizers is very restricted, growing potato (*Solanum tuberosum* L.) on sandy soils can be a major problem. A high-yielding potato crop grown in Scandinavia needs at least 200 kg K ha^{-1} to produce 40 Mg tubers ha^{-1} (Svanberg, 1971), whereas the weathering capacity of a light-textured soil suitable for potato is commonly less than 5 kg K ha^{-1} yr^{-1} (Holmquist et al., 2003). Therefore, in organic cropping systems without access to animal manures, lack of available K can substantially restrict growth of crops such as potato. These few examples stress the importance of using management methods specific for each nutrient to avoid problems associated with accumulation and/or depletion. It is also quite clear that the problems are different in organic and conventional cropping systems (Bengtsson et al., 2003).

An important consideration when comparing leaching between different systems, in this case organic and conventional cropping systems, is how the systems are managed. As far as possible, it is necessary to establish systems where the only difference is in the technology used. In a thorough review of studies dealing with N leaching in organic and conventional farming systems, Kirchmann and Bergström (2001) found that very few experiments allowed an appropriate comparison. A common problem was that organic farms were compared with poorly managed conventional farms, and the intensity in N inputs was much less in the organic farms. Such differences should be taken into account to obtain relevant and conclusive comparisons (Kirchmann and Bergström, 2001), even though it may be difficult when comparing organic and conventional cropping systems due to their fundamentally different approaches regarding many important aspects. Another critical issue is how leaching is estimated. In many cases, such estimates are not based on direct measurements, but simply on nutrient budgets. The problems associated with such estimates are quite obvious since the calculated N surpluses in the budgets are only indicators of the potential losses from the systems and nothing is usually known about the partition between different losses (leaching, denitrification, and volatilization) (Dalgaard et al., 1998). In other studies, leaching estimates are based on concentrations obtained from soil water samples in porous suction cups and water flux calculations with simulation models (e.g., Stopes et al., 2002). The uncertainty in such estimates is also quite large.

The overall objective of the study presented in this paper was to investigate possible environmental benefits associated with organic cropping systems with and without addition of animal manure, especially related to water quality. The specific objectives were to: (i) estimate leaching of N, P, and K in a soil cultivated according to organic cropping principles where organic manures were used and compare the results to those measured in conventional cropping systems; (ii) estimate yields and crop uptake of these macronutrients to assess their availability under the different management regimes; and (iii) obtain knowledge on nutrient budgets (N, P, and K) in the cropping systems. Measurements were performed in individually tile-drained plots on a sandy soil in southern Sweden.

MATERIALS AND METHODS

Experimental Field and Drainage Measurements

The research site is located in southern Sweden (56°29′ N, 13°0′ E), where the seven tile-drained plots used in this study were installed (Fig. 1); two in 1982, three in 1989, and two in 1996. The soil at the site is a sandy loam (Fluventic Haplumbrept) according to the USDA soil classification system. The field has been cultivated for over 150 yr, with cereals and forage crops being the most common crops grown. Some physical and chemical soil properties are listed in Table 1. The independently tile-drained plots have a surface area of 0.09 ha (30 by 30 m), except those that were installed in 1982, which are 0.16 ha in size (40 by 40 m). The drainage pipes are placed at an average depth of 0.9 m and with a spacing of approximately 7 m between pipes. To prevent water flowing from surrounding areas and mixing with the tile drainage water captured in each plot, drainage pipes were installed 1.5 m outside a set of every three to four plots. Drainage from each plot was led to a measuring station where discharge rates were recorded with tipping buckets and water samples were collected. The number of times the tipping buckets were emptied was recorded on a data logger, which stored accumulated daily drainage volumes from each plot. Daily values of precipitation and average temperature were also recorded at the site.

Experimental Treatments

Two 6-yr organic cropping systems were studied, one with and one without addition of animal manure. In the latter, N was provided from green manures. For comparison, two conventional systems without addition of animal manure were included; in one of these, cover crops were grown each year. Hereafter, the systems are referred to as: OAM (organic with animal manure), OGM (organic with green manure), CON (conventional), and CCC (conventional with cover crops). The conventional systems have been in place since 1982 to study the long-term effects of cover crops on leaching. Three plots established in 1992 were managed to simulate organic cropping systems associated with dairy production. While animals were not allowed to graze on these plots, liquid manure was applied periodically to a representative cropping sequence. The application rate of animal manure was determined by the maximum stocking rate that the fodder production of the plots allowed. The organic system without addition of animal manure, but with green manure, was started in 1997 on two plots. The sequence of crops in each system, the type and timing of tillage practices, and harvest times are listed in Table 2.

In the conventional system with cover crops, perennial ryegrass (*Lolium perenne* L.) was insown in spring, at the same time as the main crop, and incorporated into soil the following spring. However when potato was grown, winter rye (*Secale cereale* L.) was used as the cover crop and was established as soon as possible after harvest in autumn. In October 2001, the cover crop was treated with glyphosate [*N*-(phosphonomethyl)glycine] to keep the weed level down. The legume-based green manures [a mixture of red clover (*Trifolium*

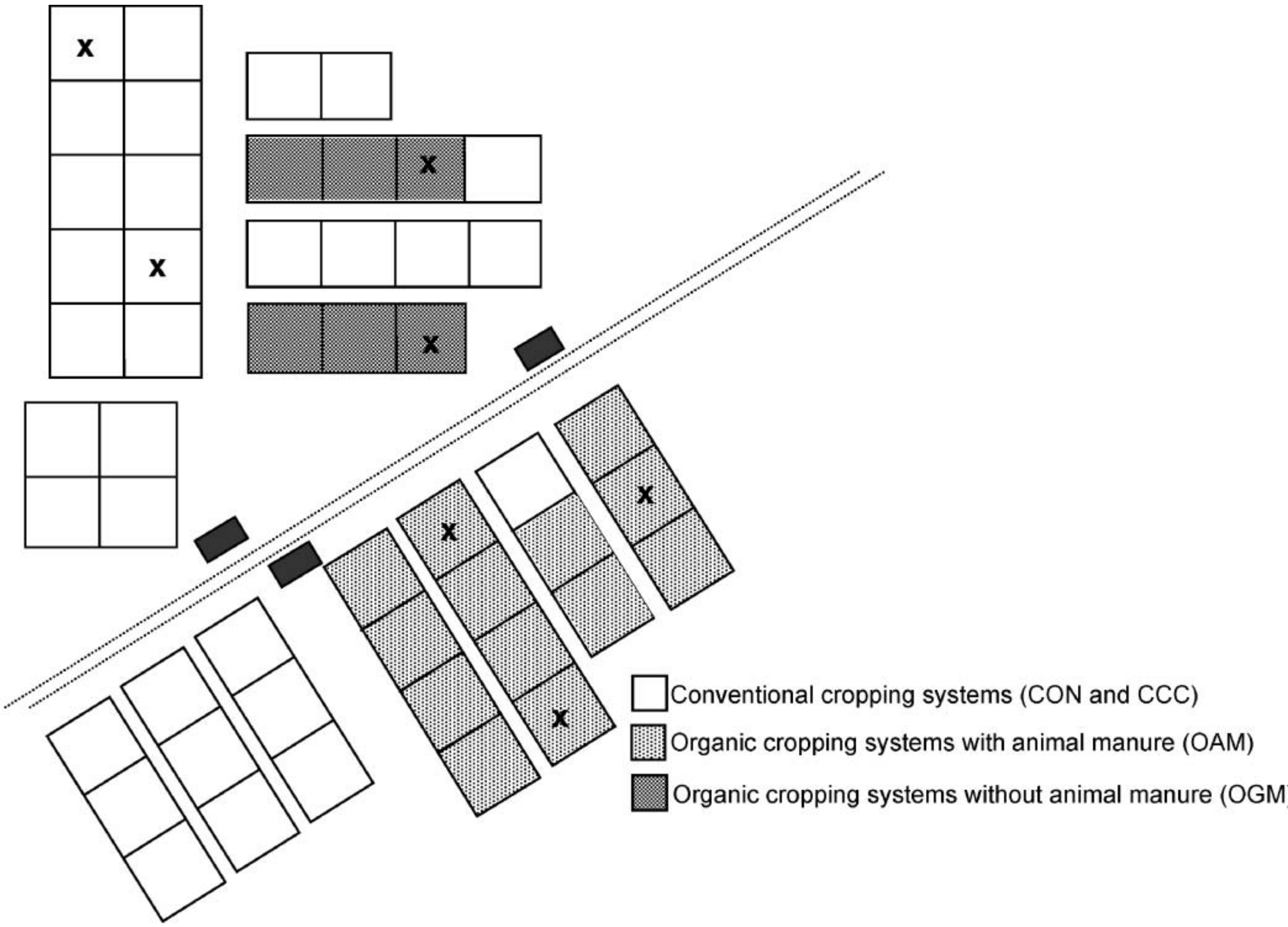

Fig. 1. Location of the tile-drained plots (x) in the experimental field.

pratense L.), perennial ryegrass, and meadow fescue (*Festuca pratensis* Huds.)] grown in the organic systems and the forage crops (a mixture of red clover and meadow fescue) in the OAM rotation also largely functioned as cover crops by taking up inorganic N during autumn/winter. Taking this into account, the CON system never had the soil covered with vegetation in late autumn, whereas the CCC and OAM systems always had the soil covered. The OGM system had a soil cover in late autumn during 5 of the 6 yr.

The liquid manure used in the OAM system was obtained from a dairy farm located close to the experimental plots. The manure was applied on the soil surface in bands 37.5 cm apart. Within 5 h, the manure was incorporated into soil if spring-sown cereals or potato were grown. In other cases, it was spread in bands in the growing crop and was not incorporated. Before application, a sample was collected from each spreader to form a pooled sample, which was analyzed for contents of dry matter (DM), NH_4–N, total N, total P, K, and total C. On average, the manure contained 6% DM and 66.7 (total N), 38.3 (NH_4–N), 10.0 (total P), and 55.0 (K) g kg^{-1} DM of each nutrient. The total C content was 42.8% of DM.

Table 1. Selected properties of the soil sampled in the organic with animal manure (OAM) plots in 1989, i.e. before the start of the experimental period described in this paper.

Soil layer	Soil texture† (Gr/Sa/Si/Cl)	Organic matter	Bulk density	pH‡	Total N	Total C	P-AL§	K-AL§
cm	%		g cm^{-3}		%		mg 100 g^{-1} soil	
0–30	0/77/14/9	4	1.45	6.2	0.16	2.3	29	9.1
30–60	0/91/7/2	1	1.64	5.7	0.04	0.6	5.4	2.3
60–90	0/86/13/1	0	1.65	5.7	0.01	0.03	2.1	2.6

† According to the USDA soil classification system (Gr = gravel, >2 mm; Sa = sand, 0.05–2 mm; Si = silt, 0.02–0.05 mm; and Cl = clay, <0.02 mm).
‡ Determined in H_2O.
§ Ammonium lactate soluble P and K.

The crops in the conventional systems received annually on average 97 kg N ha^{-1}, 24 kg P ha^{-1}, and 85 kg K ha^{-1} in spring as NH_4NO_3, $Ca(H_2PO_4)_2$, and KCl, respectively. In the organic systems, 25 kg K ha^{-1} was applied in spring every year as K_2CO_3, except in 1999 in the OGM system and in 2001 in the OAM system. In 2002, when potato was grown, 50 kg K ha^{-1} (K_2CO_3) was applied in both organic systems. The animal manure was applied in spring 1999 (29 kg NH_4–N ha^{-1}, 9 kg P ha^{-1}, and 46 kg K ha^{-1}), in spring 2001 (28 kg NH_4–N ha^{-1}, 11 kg P ha^{-1}, and 53 kg K ha^{-1}), and in spring 2002 (86 kg NH_4–N ha^{-1}, 19 kg P ha^{-1}, and 112 kg K ha^{-1}). Amounts of N, P, and K applied to the different crops in the four cropping systems are listed in Table 2.

After harvest in autumn, all plots except those with a vegetation cover, were disc-harrowed, followed by moldboard plowing to about 30-cm depth in late autumn (Table 2). In spring, the plots (except those with a growing forage crop) were tilled to 5-cm depth in preparation for planting. All grains were planted in bands.

When the potato was grown in 2002, the conventional systems were repeatedly treated with the fungicides metalaxyl-M

Table 2. Crops, harvest dates, time of main tillage operations, and fertilization in the different cropping systems.

Year	Crop	Spring plowing	Fertilizer N	Fertilizer P	Fertilizer K	Manure N	Manure P	Manure K	Harvest date	Autumn plowing
			kg ha^{-1}							
	Organic without animal manure (OGM)									
1997	Oat + insown green manure	–	0	0	25	0	0	0	15 Aug.	–
1998	Green manure	–	0	0	25	0	0	0	–	17 Dec.
1999	Spring wheat	–	0	0	0	0	0	0	18 Sept.	19 Nov.
2000	Oat + insown green manure	–	0	0	25	0	0	0	23 Aug.	–
2001	Green manure	–	0	0	25	0	0	0	–	–
2002	Potato + rye cc†	13 Mar.	0	0	50	0	0	0	3 Sept.	19 Sept.
	Organic with animal manure (OAM)									
1997	Barley + insown forage crop	25 Mar.	0	0	25	0	0	0	12 Aug.	–
1998	Forage crop	–	0	0	25	0	0	0	4 June, 22 July, 21 Oct.	–
1999	Forage crop	–	0	0	25	58	9	46	9 June, 23 July, 30 Sept.	19 Nov
2000	Oat + insown green manure	–	0	0	25	0	0	0	23 Aug.	–
2001	Pea/barley + insown green manure	17 Apr.	0	0	0	52	11	53	17 July	–
2002	Potato + rye cc	13 Mar.	0	0	50	140	19	112	3 Sept.	19 Sept.
	Conventional (CON)									
1997	Barley	–	90	18	63	0	0	0	11 Aug.	1 Sept.
1998	Oat	–	95	19	66	0	0	0	20 Aug.	16 Oct.
1999	Spring wheat	–	108	20	70	0	0	0	1 Sept.	15 Sep
2000	Barley	–	90	20	70	0	0	0	22 Aug.	1 Sept.
2001	Oat	–	90	18	63	0	0	0	30 Aug.	2 Oct.
2002	Potato	–	110	50	180	0	0	0	17 Sept.	30 Sept.
	Conventional with cover crops (CCC)									
1997	Barley + ryegrass cc	9 Apr.	90	18	63	0	0	0	11 Aug.	–
1998	Oat + ryegrass cc	21 Apr.	95	19	66	0	0	0	20 Aug.	–
1999	Spring wheat + ryegrass cc	14 Apr.	108	20	70	0	0	0	1 Sept.	–
2000	Barley + ryegrass cc	19 Apr.	90	20	70	0	0	0	22 Aug.	–
2001	Oat + ryegrass cc	17 Apr.	90	18	63	0	0	0	30 Aug.	–
2002	Potato + rye cc	10 Apr.	110	50	180	0	0	0	17 Sept.	–

† cc, cover crop.

[methyl *N*-(2-methoxyacetyl)-*N*-(2,6-xylyl)-DL-alaninate] and fluazinam [3-chloro-*N*-(3-chloro-5-trifluoromethyl-2-pyridyl)-α,α,α-trifluoro-2,6-=dinitro-*p*-toluidine] during the growing season.

Harvest and Analyses of Crop Samples

The cereal and forage crops were harvested with a combine, which was driven three times over each plot, perpendicular to the drainage pipes, to collect individual samples for each plot. Grain and stover were separated and analyzed individually. To determine the potato yield, six 20-m-long rows were harvested in each plot. In the conventional systems, stover was removed from the plots after harvest. In the organic systems, stover was returned and mixed with the topsoil in each plot, except in those plots that had a forage crop after harvest of barley (*Hordeum vulgare* L.) in 1997. The reason for this difference between the conventional and organic systems was that stover removal is conventional practice in Sweden in cover crop systems, whereas stover is normally returned to soil in organic cropping systems.

At harvest, samples of cereal grain and stover, biomass of forage and cover crops, and above- and belowground parts of potato plants were collected. Before analysis, all samples were dried at 50°C and weighed. Potato samples were also washed before further preparation.

The N content in the crop samples was analyzed by combustion on an elemental analyzer (Leco CNS-2000, Leco Corp., St Joseph, MI; Kirsten and Hesselius, 1983), whereas P and K contents were analyzed with ion-coupled plasma (ICP) after digestion with H_2SO_4.

To determine the total N and C contents on forage and cover crops that were growing after harvest of the main crop, plant material of these crops was sampled three times in autumn/spring each year. Aboveground plant parts were cut at ground level in nine randomly selected 0.25-m^2 squares in each plot. These samples were then pooled into three subsamples for each plot, which were analyzed with an elemental analyzer (Leco CNS-2000).

Collection and Analysis of Water Samples

After every 0.2 mm of drainage water had discharged through the drainage pipes entering the measuring station, 15-mL subsamples were collected by a peristaltic pump into individual polyethene bottles for each plot. These flow-proportional drainage water samples were emptied every 2 wk if drainage water was available.

To determine the total N concentrations, inorganic and organic N constituents were oxidized by $K_2(SO_4)_2$ + NaOH to NO_3 (Stevenson, 1982), which was analyzed by flow-injection analysis (Model 5012 analyzer; Tecator AB, Höganäs, Sweden) according to the colorimetric Cd-reduction method (APHA, 1985). The total P concentrations were determined on unfiltered samples according to methods issued by the European Committee for Standardization (ECS, 1996). Potassium concentrations were determined on unfiltered samples by atomic absorption (PerkinElmer 2280, Norwalk, CT) at 422.6 nm.

Collection and Analysis of Soil Samples

Soil samples from each plot were collected about four times each year. The samplings were timed to coincide with important phenological stages of the crops or with periods when there was reason to expect essential changes in mineral N content in the soil profile (i.e., early in spring, 2–3 wk after crop emergence, at yellow ripeness of cereals, and in late October/early November).

In each plot, soil was collected with a tube drill from three layers (0–0.3, 0.3–0.6, and 0.6–0.9 m). In the topsoil (0–0.3 m), 24 samples were collected in each plot, whereas in the layers below, 12 samples were collected. The individual samples were then mixed by layers into a pooled sample for each layer and plot. After collection, the samples were stored in a freezer (−20°C). For analysis, the thawed, moist soil was weighed and extracted with 2 *M* KCl. The concentrations of NO_3–N were determined in the extracts as described above for water samples. Concentrations of NH_4–N in the soil extracts were determined using a combined flow-injector gas-diffusion method (Tecator, 1984) in which the extract is injected into a carrier stream and mixed with 0.1 *M* NaOH solution. The analytical values were converted to N kg ha^{-1} using dry bulk densities and water contents specific for each layer.

Calculations and Statistical Analysis

The daily leaching load of each constituent was calculated by multiplying the concentrations in each sample by the daily amounts of drainage during the 2-wk period before the sampling date. These daily loads were then added together to give the annual leaching load (from 1 July to 30 June the following year) of each constituent. The yearly average concentrations were obtained by dividing the accumulated yearly load by the annual amounts of drainage from each treatment (represented by one to three plots).

The two conventional cropping systems contained no replicates but were treated in the same way each year, except that cover crops were grown in one of the systems. To analyze differences in leaching, and yields and nutrient contents of crops statistically, pairwise *t* tests were performed for differences between means for the period 1997 to 2003 by using years as replicates (MINITAB version 14.1). The two organic cropping systems, which contained two or three replicates, were also compared by pairwise *t* tests of differences in average leaching of N, P, and K for the period 1997 to 2003. Statistical comparisons between the conventional and organic systems were limited to the CCC and OGM systems. Differences between means of yield and between crop uptake and leaching of N, P, and K in these systems were compared by pairwise *t* tests by using years when grain crops were grown as replicates (1997, 1999, and 2000; MINITAB version 14.1). The experimental treatments were arranged in a completely randomized design within each treatment block (CON + CCC, OAM, and OGM; Fig. 1).

RESULTS AND DISCUSSION

Precipitation and Drainage Conditions

Annual average precipitation during the 6-yr period was 851 mm, which was slightly higher than the long-term average precipitation in the area (773 mm yr^{-1}). The wettest and driest years had precipitation of 1191 and 617 mm, respectively (Fig. 2). The mean annual drainage from the plots varied between 259 and 358 mm (Fig. 2). As expected, in all systems, the largest amounts of drainage coincided with the wettest year (1998–1999), which is a reflection of the strong correlation between precipitation and drainage. It is notable that the smallest amount of drainage was recorded in all systems during a year (1997–1998) with above-average precipitation (886 mm), which was largely due to the distribution of precipitation over the year. During this year, the total amount of rainfall in June 1998 was 134 mm, whereas drainage was only about 10 mm, due to high transpiration by a growing crop. In contrast, during the year 2001–2002 when precipitation was 835 mm, drainage was between 344 and 479 mm, due to the fact that precipitation was more intensive outside the cropping season in autumn/winter. A drainage pattern with most of the drainage occurring in unfrozen soil without a crop is typical of Scandinavian climatic conditions (Hansen and Djurhuus, 1996).

There was no obvious influence of the type of crop on the magnitude of annual drainage volumes in either cropping system. Such influences were overshadowed by the amounts and distribution of precipitation each year, as discussed above. Comparing the different cropping systems, the CCC system had significantly larger ($P < 0.05$) drainage volumes than the OGM when years with grain crops were considered (1997, 1999, and 2000). Of the conventional cropping systems, the average yearly amounts of drainage over the entire 6-yr period were significantly smaller ($P < 0.05$) in the CON system than in the CCC (Fig. 2). The average yearly amounts of drainage were also smaller in the OGM system than in the OAM, but the differences were not significant ($P > 0.05$). These drainage volumes represented 30 (CON), 42 (CCC), 40 (OAM), and 33% (OGM) of average annual precipitation. The larger drainage volumes in the CCC and OAM systems were unexpected since the lower crop yields (see below) in the other systems without a cover crop or animal manure (Table 3) should lower transpiration and thereby increase drainage. In the case of the cover crop effect, this could partly be attributed to improved soil structure caused by the cover crop and thereby increased water infiltration rate into the soil profile. However, in both cases, the most likely reason was spatial variability in hydrological conditions among plots, causing percolating water to bypass the tile-drains in certain parts of the experimental field, which reduced drainage volumes, whereas inflow of groundwater probably occurred in other parts, which increased drainage. The extent of tile-drainage bypass and groundwater inflow was not estimated in this study, but we are aware that there is commonly some unavoidable uncertainty in the collection of water in an underground tile-drainage system (e.g., Bergström, 1987). However, as indicated in the introduction, other ways of estimating drainage flows and leaching are also associated with uncertainties.

Leaching of Nitrogen, Phosphorus, and Potassium

Annual leaching loads of N, averaged over the whole 6-yr crop rotation, were not significantly different ($P > 0.05$) between the organic systems (OAM, 39 kg N ha^{-1}; OGM, 34 kg N ha^{-1}; Fig. 3). In both systems, the corresponding average concentrations in drainage water were 12 mg N L^{-1}. In the CON system, average annual N leaching load and the corresponding concentration were 38 kg N ha^{-1} and 16 mg N L^{-1}, respectively (Fig. 3). Adding a cover crop in this system lowered these values to 25 kg N ha^{-1} and 7 mg N L^{-1} (Fig. 3),

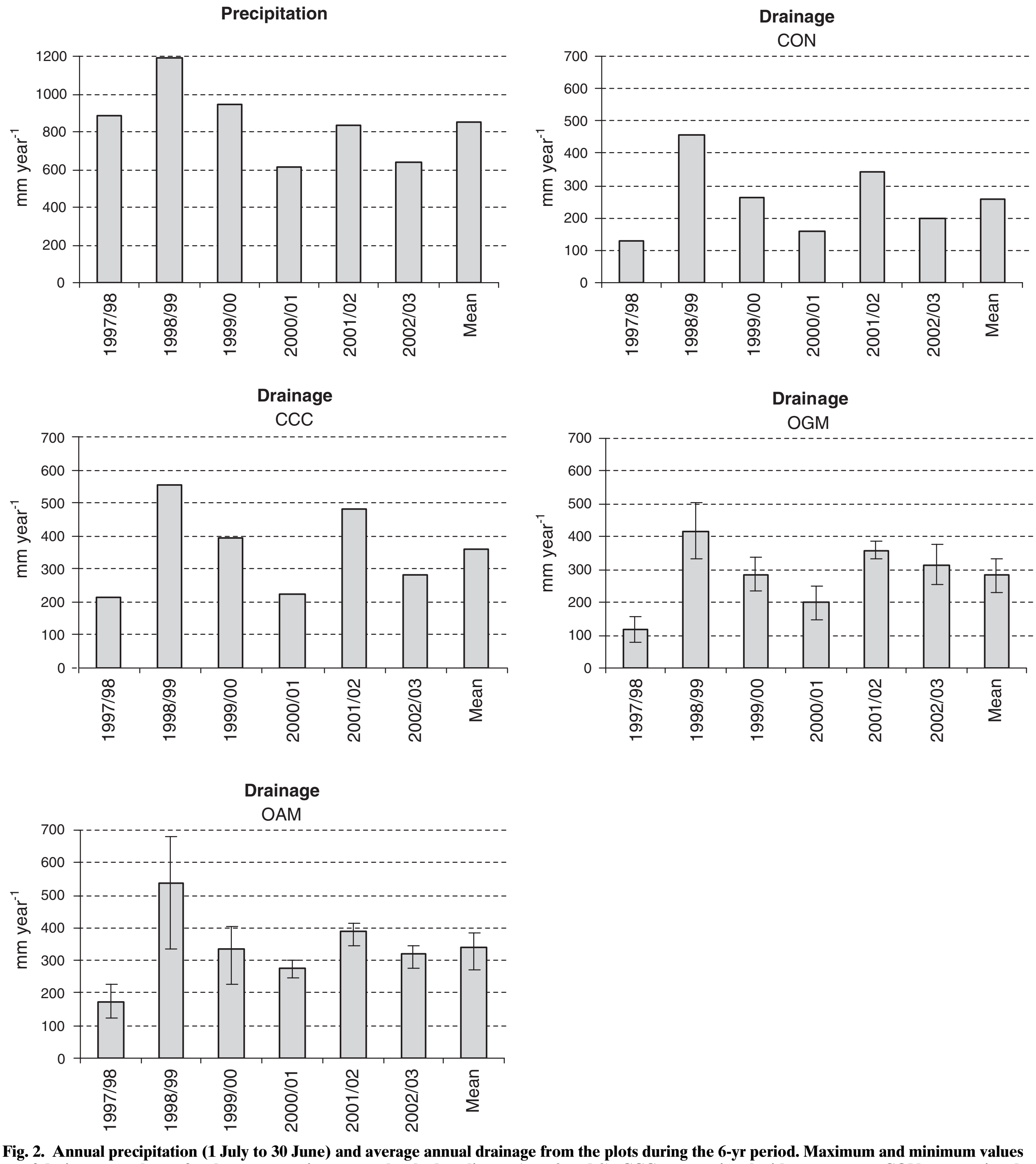

Fig. 2. Annual precipitation (1 July to 30 June) and average annual drainage from the plots during the 6-yr period. Maximum and minimum values of drainage are shown for the two organic systems that had replicates (n = 2 and 3). CCC, conventional with cover crops; CON, conventional; OAM, organic with animal manure; OGM, organic with green manure.

respectively, which were both significantly ($P < 0.1$ and $P < 0.05$, respectively) below those in the CON system. Annual average leaching load and concentration of N for years with grain crops was also significantly smaller ($P < 0.05$) in the CCC system than in the OGM. In other words, of the three cropping systems compared above, N leaching was clearly smallest in the conventional system with a cover crop. As indicated above, leaching of N was also smaller in the CCC system than in the OAM, even though it was not statistically verified. It is important to stress that the conventional cover crop system is the one with which the organic systems should be

Table 3. Harvested crop yields (grain, tubers, and forage; ± standard deviation in the two organic farming systems; n = 2 and 3) and content of N, P, and K. Yields of cereals correspond to a water content of 15% while yields of potato and forage crops are presented as dry weight.

Year	Conventional (CON)			Conventional with cover crops (CCC)			Organic without animal manure (OGM)			Organic with animal manure (OAM)		
	kg ha^{-1}											
1997	4060 (barley)			4480 (barley)			2970 (±297) (oat)			2133 (±463) (barley)		
1998	5390 (oat)			5850 (oat)			- (green man.)			9263 (±627) (forage crop)		
1999	5990 (spring wheat)			5780 (spring wheat)			4615 (±7) (spring wheat)			9620 (±401) (forage crop)		
2000	4998 (barley)			5533 (barley)			2710 (±113) (oat)			4427 (± 647) (oat)		
2001	5616 (oat)			5812 (oat)			- (green man.)			7087 (±1162) (pea/barley)		
2002	8496 (potato)			9118 (potato)			1410 (±0.3) (potato)			1560 (±2.5) (potato)		
	N	P	K	N	P	K	N	P	K	N	P	K
1997	49	14	14	55	17	15	28	8	10	26	6	9
1998	62	16	18	66	17	20	–	–	–	222	29	165
1999	84	18	20	86	17	20	66	14	15	247	33	193
2000	57	15	17	68	17	19	24	6	9	56	14	18
2001	65	16	20	63	17	22	–	–	–	84	18	84
2002	96	13	133	93	19	175	27	4	32	28	4	31

compared since the organic systems had a crop cover in late autumn during 5 (OGM) or 6 (OAM) yr of the 6-yr rotation, which contributed to reducing the N-leaching loads. If a proper comparison between organic and conventional systems is to be made, well-managed forms of each system should be represented, as pointed out above.

In both organic systems and in the CCC system, the largest leaching loads occurred during 2002–2003 when potato was grown (Fig. 3). As much as 98 kg N ha^{-1} yr^{-1} leached in the OAM system, which represented about 40% of the total load during the 6-yr period. Large N-leaching loads after potato are quite common

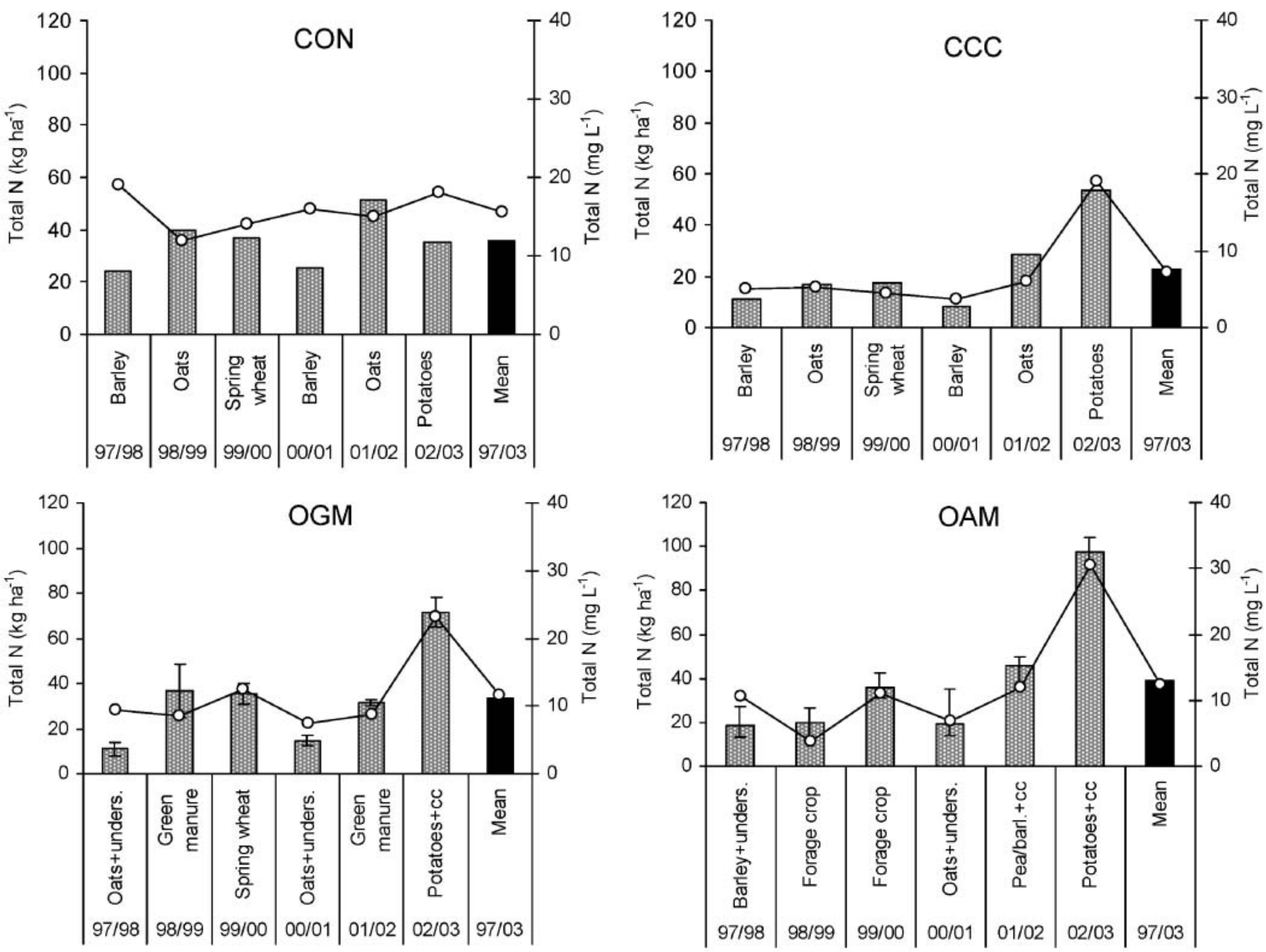

Fig. 3. Annual mean values (1 July to 30 June) of concentrations (circles) and leaching loads (columns) of total N. Maximum and minimum values of leaching are shown for the two organic systems that had replicates (n = 2 and 3). CCC, conventional with cover crops; CON, conventional; OAM, organic with animal manure; OGM, organic with green manure.

(e.g., Madramootoo et al., 1992), due to a number of factors such as shallow root system, large fertilizer N applications to obtain optimal yield, intensive tillage operations before planting and after harvest, a relatively short N uptake period, and sprinkler irrigation to meet water requirements. In addition, potato is commonly grown on coarse-textured soils, such as that used in this study, which are susceptible to leaching (Bergström and Johansson, 1991). However, the large N-leaching loads in the organic cropping systems included in this study were primarily caused by the extremely low potato yields (see below), and thereby small N crop uptakes. Large amounts of N released from the green manure, which was plowed under in spring before potato, were planted in the OGM system, and the animal manure, which was incorporated into soil in the OAM system, also contributed to the large N-leaching loads when potato was grown.

Overall, annual average concentrations and leaching loads of P were very small (Fig. 4). Averaged over the 6-yr period, they reached 0.06 mg L^{-1} and 0.23 kg ha^{-1} in the OAM system. However, these values were not significantly ($P > 0.05$) larger than those in the OGM system. The tendency for larger losses in the OAM system was probably due to the fact that manure was applied in this system, whereas P was never added in the OGM system. A further contributing factor was probably the peak in P leaching that occurred in the OAM system during 1998–1999 (Fig. 4) when the grass/clover forage crop grown was exposed to early freezing. Increased P leaching has been observed in many studies as a result of freezing of fresh plant material and subsequent disruption of cell membranes (e.g., Timmons et al., 1970; Miller et al., 1994). Of the two conventional systems, the CCC system had significantly larger P-leaching loads ($P < 0.05$) than the CON (Fig. 4), most likely also as a result of early freezing of fresh plant material during autumn. An alternative explanation could be increased water infiltration in soil, as suggested above. The CCC system also had significantly larger P-leaching loads ($P < 0.1$) than the OGM system when years with grain crops were considered.

Over the 6-yr period, annual average concentrations and leaching loads of K in the organic systems reached

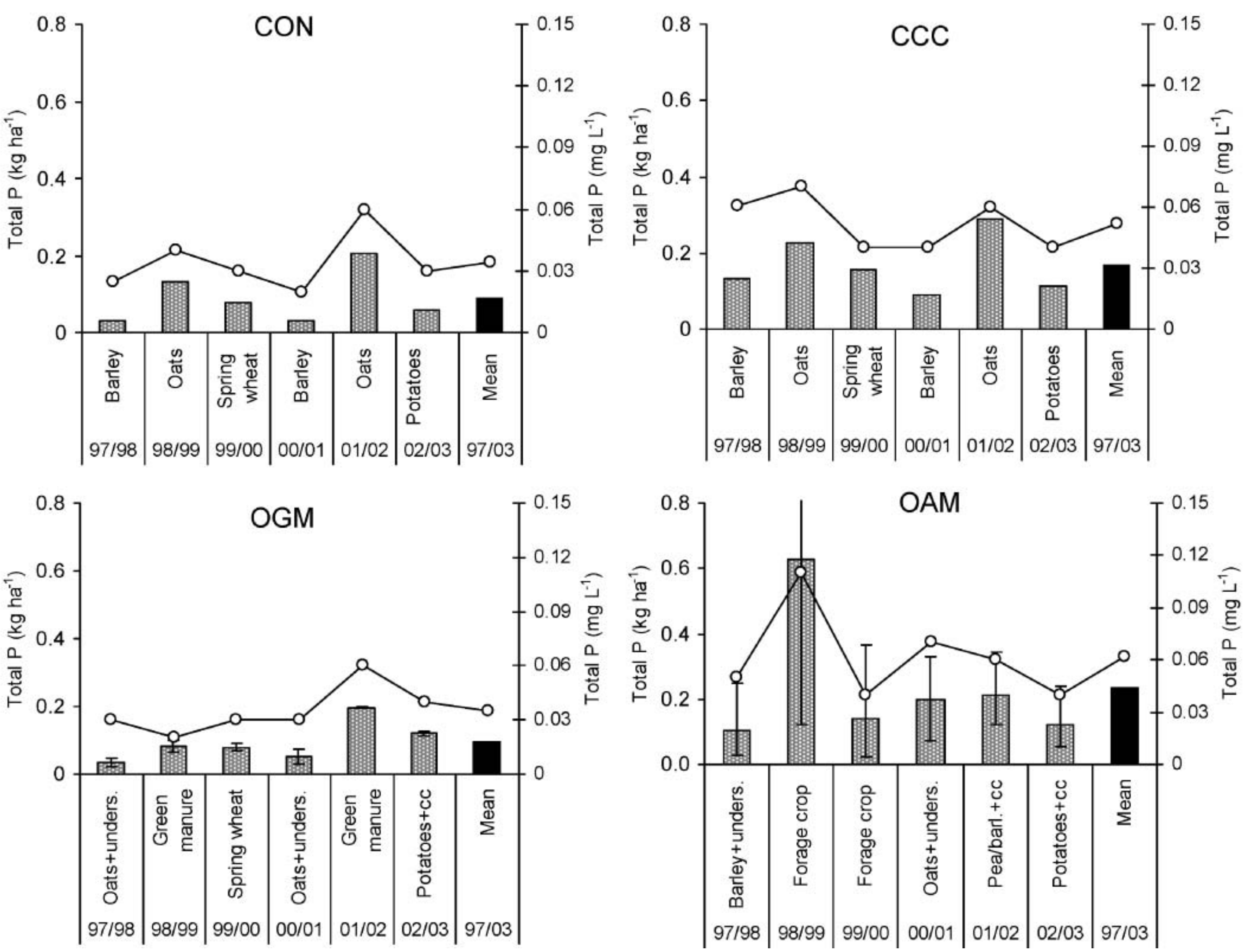

Fig. 4. Annual mean values (1 July to 30 June) of concentrations (circles) and leaching loads (columns) of total P. Maximum and minimum values of leaching are shown for the two organic systems that had replicates ($n = 2$ and 3). CCC, conventional with cover crops; CON, conventional; OAM, organic with animal manure; OGM, organic with green manure.

6 mg L^{-1} and 16 kg ha^{-1} in the system without animal manure (Fig. 5), but the differences between the two systems were not significant ($P > 0.05$). The corresponding concentrations and loads of K in the conventional systems were 9 mg L^{-1} and 23 kg ha^{-1} in the CON system and 8 mg L^{-1} and 27 kg ha^{-1} in the CCC system (Fig. 5), of which the leaching load was significantly larger ($P < 0.05$) in the latter. The CCC system also had significantly larger average annual K-leaching load ($P < 0.05$) than the OGM system, again, when grain crops were considered. The larger load of K in the conventional system than in the organic was presumably caused by the larger inputs of K in the conventional system; the OGM system only received 25 kg K ha^{-1} yr^{-1} with fertilizer (Table 2).

Yearly differences in K leaching within systems appeared to be due largely to differences in drainage volume, as K concentrations in drainage water remained relatively constant (Fig. 5). In contrast, leaching of N and P within systems was, to a large extent, dependent on the concentrations of N and P in drainage water, so that during years with large leaching loads, concentrations of N and P were usually high (Fig. 3 and 4). For example, the large N-leaching loads in the CCC, OAM, and OGM systems during 2002–2003, when potato was grown, were primarily caused by the high N concentrations in drainage water (Fig. 3).

Mineral Nitrogen in Soil

The amounts of mineral N in soil varied widely between different sampling occasions, especially in the organic cropping systems (Fig. 6). In most years, the amounts of mineral N in soil were smallest at the time of harvest and then increased during autumn, but in the CCC system, the amounts remained small (<30 kg N ha^{-1}). However, when the cover crop was treated with glyphosate in October 2001, and when rye was used as a cover crop after potato, mineral N in soil increased during autumn. In the conventional cropping systems, mineral N in soil never exceeded 80 kg N ha^{-1}, whereas in the organic cropping systems, the soil on some sampling occasions contained about 150 kg N ha^{-1} down to 0.9-m depth. In the OGM system, incorporation of the green manure into soil in December 1998 and March

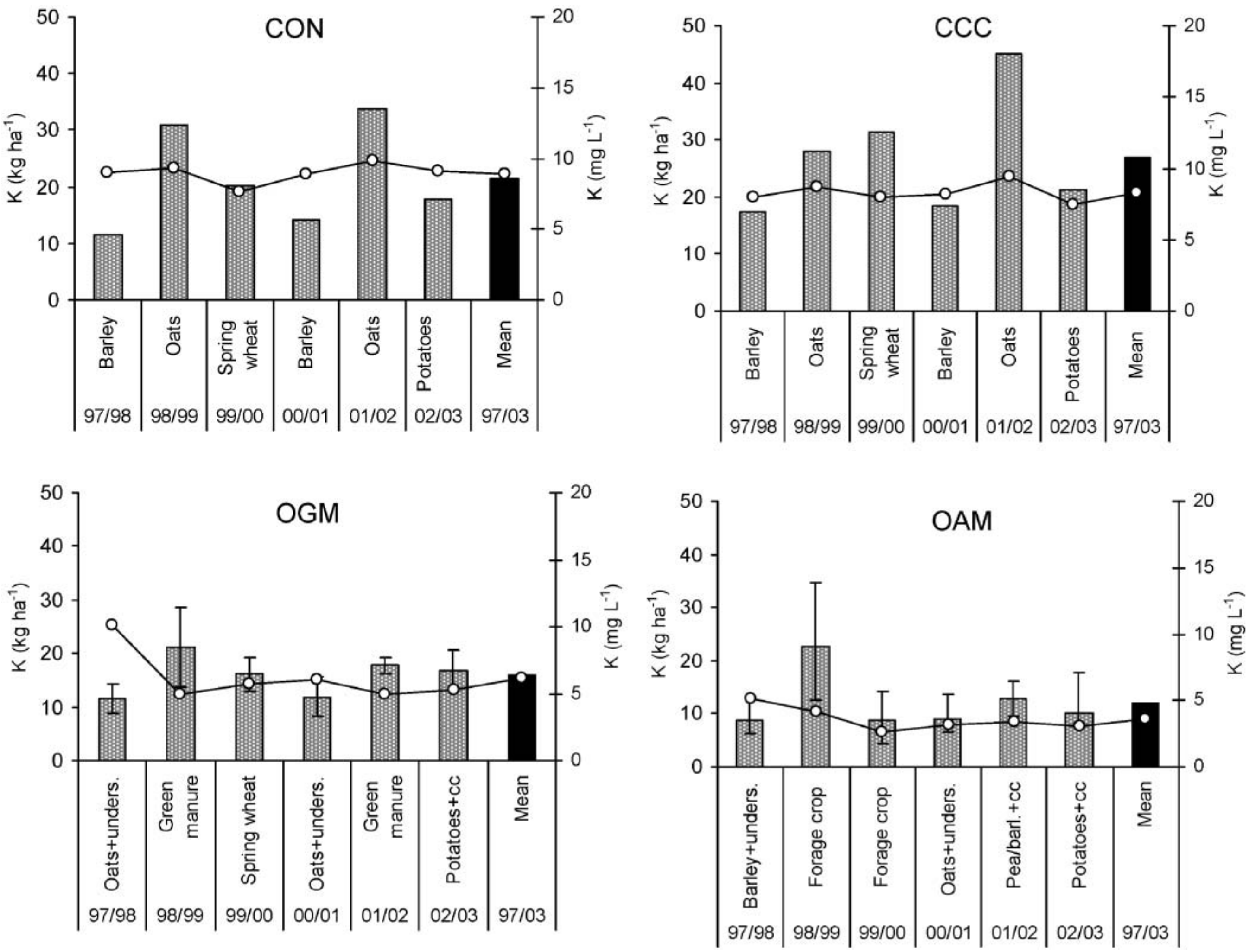

Fig. 5. Annual mean values (1 July to 30 June) of concentrations (circles) and leaching loads (columns) of K. Maximum and minimum values of leaching are shown for the two organic systems that had replicates ($n = 2$ and 3). CCC, conventional with cover crops; CON, conventional; OAM, organic with animal manure; OGM, organic with green manure.

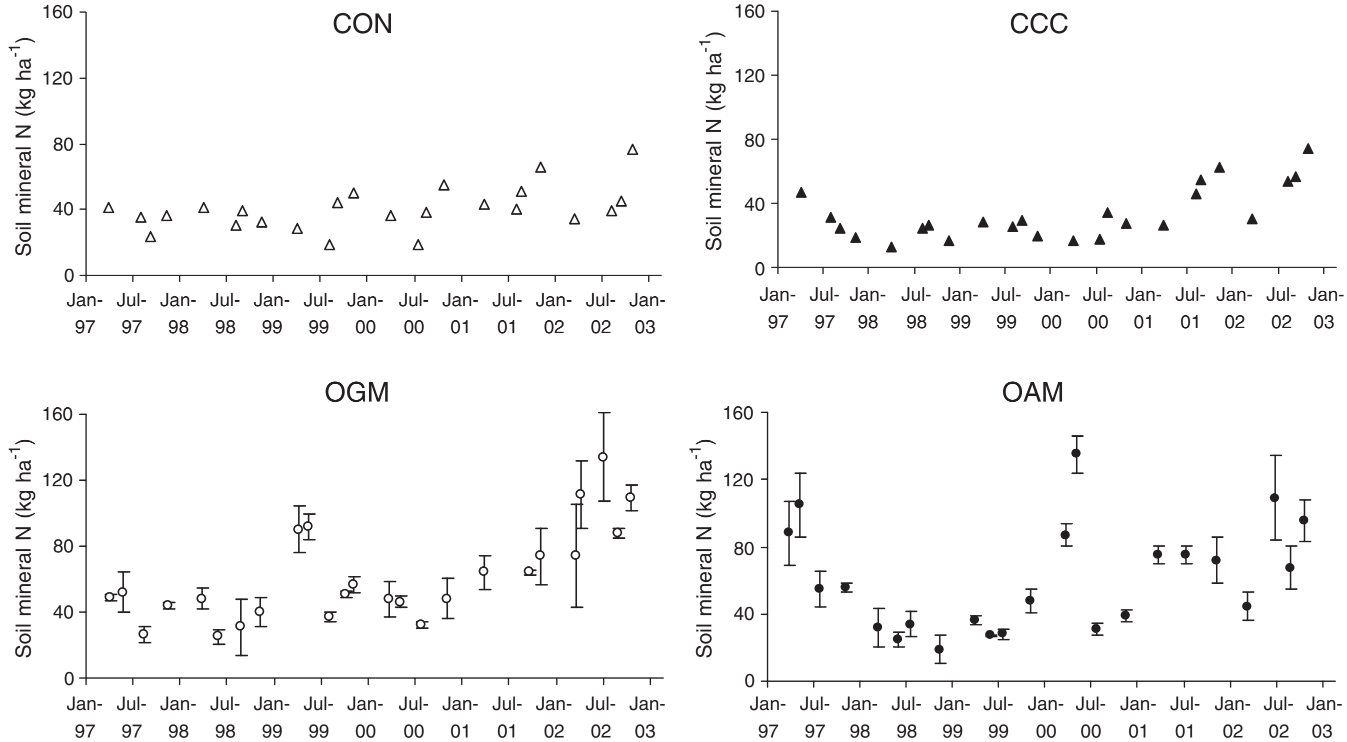

Fig. 6. Mineral N content in the soil profile down to 0.9-m depth during the experimental period. Maximum and minimum values are shown for the two organic systems with replicates (n = 2 and 3). CCC, conventional with cover crops; CON, conventional; OAM, organic with animal manure; OGM, organic with green manure.

2002 resulted in accumulation of mineral-N in soil during the subsequent spring, presumably due to increased N mineralization. Furthermore, in the OAM system, incorporation of the clover/grass forage crop in November 1999 resulted in large amounts of soil mineral N in the following spring.

The tendency for larger fluctuations in mineral N content in soil in the organic cropping systems and the higher mineral N peaks in these systems in spring are reflections of the fact that inorganic N was largely released from the organic manures during periods with no crop uptake, and such N is very exposed to leaching in cold humid regions (Bergström and Kirchmann, 2004). In this study, the green and animal manure incorporations into soil in spring before planting potato clearly contributed to elevated N leaching loads in the organic systems, as mentioned above.

Yields and Nutrient Contents of Crops

Crop yields in the four different cropping systems are presented in Table 3, together with the N, P, and K contents of harvested products. In addition, on average, 2300 kg of dry weight (7.8 kg of N, 2.4 kg of P, and 28 kg of K) and 3100 kg of dry weight (14 kg of N, 4.1 kg of P, and 41 kg of K) per hectare and year was removed with straw from the CON and CCC systems, respectively. The short-term impact on yields of removing straw in the conventional systems but not the organic was probably limited since only small amounts of nutrients were added with straw. In terms of N, on average, only about 5 kg N ha^{-1} yr^{-1} derived from cereal straw in the OGM system over the 6-yr period. However, over the long term, repeated incorporation of straw would most likely lead to a buildup of organic N in soil and thereby possibly increased crop N uptake.

The average annual yield over the 6-yr period was significantly higher ($P < 0.05$) when a cover crop was included in the conventional systems, whereas the difference in harvested N with crops was not ($P > 0.05$). This is in contrast to many other studies that have shown that intersown cover crops in cereals, such as perennial ryegrass in barley, slightly reduced barley yields (Jensen, 1991; Andersen and Olsen, 1993). However, other studies with a barley–ryegrass system showed no significant difference in yield compared with barley alone (Bergström and Jokela, 2001). Lack of yield reductions has also been shown for corn (*Zea mays* L.) when rye was used as an intersown cover crop on a sandy loam soil in Michigan (Rosse et al., 2000). A comparison of crop yields in the organic systems was not attempted due to the fact that the crop rotations were so different.

Comparison of crop yields between the conventional and organic systems was also rather difficult. However, in some years, the same crops were grown [barley in 1997; spring wheat (*Triticum aestivum* L.) in the CON, CCC, and OGM systems in 1999; and potato in 2002]. In those years, the crop yields were always lower in the organic cropping systems than in the conventional. The barley yield in the OAM system in 1997 was only 50% of that in the conventional plots. The grain DM yield of spring wheat (grown in 1999) in the OGM system was about 80% of that in the conventional systems, whereas N concentrations of grain were almost the same (data not shown). Considering the average annual yield of the grain crops grown in 1997, 1999, and 2000, it was significantly higher ($P < 0.1$) in the CCC system than in OGM, which was also the case for harvested N with crops ($P < 0.05$). This indicates that the N release from the green manure, which was incorporated into soil in December 1998, was not adequate for crop requirements. Overall, there were small differences in the average concentrations of N, P, and K in harvested crops between the different cropping systems (data not shown), with the exception of the forage crops in the OAM system. Their tissue concentrations of N and K were about 2%, which was considerably higher than the corresponding average concentrations in the other systems. Yields of potato in 2002 were very low in the organic systems due to severe damage by the potato blight fungus *Phytophthora infestans*. In the conventional systems, this problem was eliminated by use of fungicides, and the yields of potato were accordingly much larger. Large yield reductions in organically grown potato have been observed throughout southern Sweden in some years (SCB, 2004).

A widespread reduction in crop yields in future agriculture around the world has to be taken seriously. Despite considerable improvements in crop yields and food security in large parts of the world during the last 50 yr, a large proportion of the population in developing countries is still undernourished and will continue be at risk of malnutrition in the future (FAO, 2005). Therefore, it is critical to maintain sufficient land area for crop production and, if possible, increase the productivity per unit land area without jeopardizing environmental quality. In this context, it is questionable whether organic crop production is a viable alternative. Results from this study showed that crop yields in organic systems were reduced by 20 to 80% compared with the same crops grown in conventional systems. Several other studies have also measured large yield reductions for organically grown crops (e.g., Leake, 1999, 2000). These examples indicate that organic crop production uses farmland less efficiently.

Nutrient Balances

Inputs and outputs of N, P, and K to the different cropping systems (excluding deposition, denitrification losses, and NH_3 volatilization from the green manure) are shown in Table 4. Excluding some important nutrient flows in a field balance, as was done here, is certainly a simplification. However, the main objective of looking at nutrient balances in this case was to compare the cropping systems with regard to major nutrient flows that were expected to be different between the systems. Deposition of N, which is about 15 kg ha^{-1} yr^{-1} in this region of Sweden (SEPA, 2005), is the same over the entire experimental field. Annual denitrification estimates have never been determined at the site, but such losses should be minimal considering that denitrification losses are typically small from well-drained sandy soils (Groffman and Tiedje, 1989). Runoff losses have never been observed at the site due to the flatness of the field in combination with the large infiltration capacity of the soil (Jarvis and Messing, 1995).

For N, all cropping systems except the OGM system had negative balances, reaching on average −35 kg ha^{-1} yr^{-1} in the OAM system. The positive N balance in the OGM system was primarily due to the very small amounts of harvested N (on average 24 kg N ha^{-1} yr^{-1}). However, we have to bear in mind that the uncertainty in estimated N fixation inputs in both organic systems and the fact that NH_3 volatilization from the cut green manure plant parts was ignored make the N balances very uncertain in these systems.

To make a long-term evaluation of N leaching in cropping systems in which green manures are used, we need to consider certain practical factors in the systems. First, green manures are not applied every year, whereas inorganic fertilizers are typically applied on a yearly basis. Second, under temperate and cold temperate conditions, such as in Scandinavia, a significant input of N

Table 4. Balances of N, P, and K for the different cropping systems. The values presented refer to annual averages for the whole 6-yr crop rotation (1997–2003).

	Conventional (CON)			Conventional with cover crops (CCC)			Organic without animal manure (OGM)			Organic with animal manure (OAM)		
Inputs/outputs and balance	N	P	K	N	P	K	N	P	K	N	P	K
	kg ha^{-1} yr^{-1}											
Inputs												
Synthetic fertilizer	97	24	85	97	24	85	–	–	25	–	–	25
Manure (total N)	–	–	–	–	–	–	–	–	–	42	6.5	35
Estimated N fixation	–	–	–	–	–	–	71†	–	–	79†	–	–
Total inputs	97	24	85	97	24	85	71	0	25	121	6	60
Outputs												
Harvest	77	17	65	86	21	86	24	5.5	11	111	17	84
Leaching	38	0.1	23	25	0.2	27	34	0.1	16	39	0.2	12
NH_3 volatilization	–	–	–	–	–	–	–	–	–	6‡	–	–
Total outputs	115	17	88	111	21	113	58	6	27	156	17	96
Balance	−18	7	−3	−14	3	−28	13	−6	−2	−35	−11	−36

† Calculated with a simple model (STANK), which is based on harvested N with the legume crop and various N transfers from the legume to other components of the soil/plant system (Frankow-Lindberg, 2003).
‡ Measured with passive diffusion samplers (Svensson, 1993).

through green manure crops to soil presumes vital crop development during one summer period. This means that a green-manure period is a full growing season without harvest of other crops. In Swedish organic farming systems without animals, the frequency of green manure crops can be 1 out of 7 yr, or as often as 2 out of 6 yr in a crop rotation, as was the case in this study, which means that the allocated production area is between 14 and 33%. If we take the above-mentioned conditions into account, leaching of N measured in this study represented 59% of total N removal (leaching plus harvested N with crops) during the 6-yr period. In other words, leaching loads of N were larger than the amounts of N removed by crops. In the CON system, in which inorganic N fertilizers were applied but not green manures, N leaching was 33% of total N removal. Use of cover crops to further reduce N leaching resulted in N leaching making up only 22% of what was removed in total. What these results clearly suggest is that N use efficiency is less if green manures are used rather than inorganic N fertilizers. In this study, crop utilization of N in harvested products was, on average, 71 (CON) and 74% (CCC) in the conventional systems over the 6-yr period and 34% in the OGM system. In the OAM system, leaching of N represented 25% of total N removal (including NH_3 volatilization from the animal manure), and the N use efficiency was 91%. However, this estimate included N removal by two forage crops, which was on average 234 kg N ha^{-1} yr^{-1}. Excluding these crops to make a comparison with the other systems more relevant increased N leaching to 48% of total N removal.

The P balances were negative in both organic systems, whereas in the conventional systems, they were positive. This was expected since no external inputs of inorganic P fertilizer occurred in the organic systems and only about 6 kg P ha^{-1} yr^{-1} was applied with manure in the OAM system. A contributing factor to the still rather large amounts of P in harvested crops in the OAM system was the high level of plant available P in the topsoil (Table 1) caused by repeated applications of P fertilizer before this study.

The K balances were negative in all cropping systems, especially in the OAM system, which had a negative balance of −36 kg K ha^{-1} yr^{-1}. The K in harvested crops was, on average, relatively high in this system (84 kg K ha^{-1} yr^{-1}), mainly due to large amounts of K taken up by the forage crops (Table 3), which contributed to the large negative balance. Another contributing factor to the negative K balances in all systems was the fact that, in contrast to P, the amounts of plant available K in soil were small (Table 1). This is the main reason why, on average, 25 kg K ha^{-1} yr^{-1} (as K_2CO_3) was applied to the organic cropping systems to avoid complete crop failure. However, whether this was enough to maintain a reasonable K status in soil over the long term is questionable. In the OGM system, harvested K with crops was, on average, only 11 kg ha^{-1} yr^{-1}, which indicates that adding K to this system would substantially increase crop yields, especially of potato. As mentioned above, yields of potato were very low in both organic systems (Table 3), primarily due to potato blight and the absence of fungicide treatment. However, another contributing factor was most likely K deficiency in these systems. The amount of K in harvested potato in 2002 was only about 30 kg ha^{-1} in the organic systems, whereas it exceeded 130 kg ha^{-1} in the conventional systems (Table 3).

Over the long term, inputs and outputs of nutrients must be in balance to maintain high productivity of a soil, irrespective of whether the soil is managed according to organic or conventional principles. Even if recycling of nutrients is optimized at each farm, there will always be losses that need to be replenished, of which off-farm sales of harvested goods (grain, hay, milk, meat, etc.) are in most cases the largest. If inputs and outputs are balanced, there is a better chance of providing the crops with sufficient amounts of essential nutrients and of avoiding large losses that can cause pollution of the environment.

CONCLUSIONS

This study showed that the use of green and animal manures in organic cropping systems resulted in lower yields, and thereby reduced food supply to feed the people of the world, with almost no benefit for water quality. Therefore, claims about water quality benefits associated with the use of manures should be viewed with great caution. This is especially critical for N due to the often poor synchronicity between release of inorganic N from the manures and N uptake by the crop. Indeed, one of the most important considerations in efforts to reduce N leaching from agricultural soils is to supply the crop with N when it is needed and to avoid large amounts of N in soil during autumn/winter when no crop is growing. One way of reducing N in soil in autumn/winter, and thereby the risk of N leaching, is to use cover crops. In this study, the smallest leaching load by far was measured in the conventional system with a ryegrass cover crop, which also had the largest crop yields. This shows that as long as inorganic fertilizers are readily available, it is much more efficient to use countermeasures such as cover crops to reduce N leaching in rotations with annual crops than to change to organic-farming practices. In fact, the N use efficiency of added N in the arable crops was worse in the organic systems included in this study than in the conventional systems, especially in the organic system with green manures. This is due largely to the fact that much less N is harvested with crops during a crop rotation period in systems with green manures, whereas N-leaching loads tend to be the same as in conventional systems.

Even though the current focus on the use and losses of nutrients in organic cropping systems is related to N, the long-term sustainability of such systems is likely to be more dependent on the supply of P, K, and essential micronutrients. In this study, shortage of K in the organic systems occurred within just a few years, and especially when growing potato, which requires large amounts of K. Failure of a potato crop not only affects yield, but also N leaching loads, as was well illustrated by the results presented here.

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