Plant and Soil **237:** 321–332, 2001.

Long-term changes in extractable soil phosphorus (P) in organic dairy farming systems

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Key words: depletion, nutrient balance, P-AL, sustainability

Abstract

On five farms that have been managed organically for several years, all cultivated soils were sampled on two occasions. The time span between the first and second soil sampling varied from 6 to 12 years. At the first sampling the farms had been managed organically for 3, 4, 6, 11 or 53 years. The average phosphorus (P) concentrations in topsoil (0-20 cm) extracted by ammonium-acetate lactate solution (P-AL) decreased from the first to the second sampling on all farms. At the second soil sampling, the average topsoil P-AL concentrations on the five farms were 50, 64, 65, 75 and 119 mg P kg^{-1}, which is characterised as medium (26–65 mg P kg^{-1}) or high (66–150 mg P kg^{-1}). The decrease occurred mostly in soils with high and very high (>150 mg P kg^{-1}) P-AL concentrations at the first sampling. In these samples, the average value decreased from 100 to 87 and from 188 to 151 mg P kg^{-1}, respectively. In subsoil (20–40 cm), an increase from 15 to 27 mg P kg^{-1} ($P<0.01$) in P-AL concentration was found in subsoil samples with low P-AL concentrations (0–25 mg P kg^{-1}) at the first sampling. This indicates P transfer from topsoil to subsoil. The pattern of decrease in topsoil was fairly well explained by farm level P balances. The average topsoil concentrations of P-AL were well below values for comparable conventional farms, but still at a level acceptable for crop production. Crop yields were acceptable, but the general pattern of decrease shows that in the future, some P should be supplied from external sources to avoid a further decrease, especially on the fields with lowest P-AL concentrations.

Introduction

In organic farming systems, the phosphorus (P) fertilisation is mainly based on recycling of on-farm P by use of farmyard manure (FYM), compost, green manure and mulches as P sources. A limited amount of rock phosphate or organic fertilisers may be supplied from external sources, and often some P is indirectly supplied by purchased fodder. However, the main aim is that the organic farming system is self-sufficient with regard to the supply of nutrients (IFOAM, 2000).

Nutrient balances (the difference between nutrient inputs and nutrient outputs from a system) are commonly used to assess the long-term sustainability of farming systems. Such balances may be calculated on the farm and field level, and may include all, or only the most important in- and outputs. When the sum of P in outputs is above P in inputs, there is a shortage; the opposite situation is a surplus of P at the farm or field level. Farm level P balances defined as purchased P minus P in sold products on organic dairy farms are often close to zero, whereas conventional farming systems have larger surpluses due to purchased fodder and fertilisers. A small surplus of 2 kg P ha^{-1} $year^{-1}$ was found on organic dairy farms in the study of Kerner (1993) as reviewed in Ebbesvik and Løes (1994), and a surplus of 7 kg P ha^{-1} $year^{-1}$ by Kristensen and Halberg (1995). On conventional dairy farms, a surplus of 14 kg P ha^{-1} $year^{-1}$ has been found (Gool, 1996). Internal losses of P may be considerable. Nolte and Werner (1994) found an internal P loss of 23% in an organic livestock system, probably caused by the handling of roughage and FYM. Therefore, average field level nutrient balances commonly show larger shortages than farm level balances, as quantified by two studies comparing farm and field

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level data. In one study, the P surplus was 3 kg 6 P ha^{-1} $year^{-1}$ on the farm level but only 0.5 kg at the field level (Fagerberg et al., 1996), whereas in another study the P shortage was -1.2 kg on the farm level as compared to -2.9 kg P ha year at the field level (Nolte and Werner, 1994). With lower livestock density, the nutrient shortage will increase as calculated by Eriksen et al. (1995) where an average field level P surplus of 2 kg P ha^{-1} $year^{-1}$ decreased to a shortage of -4.5 kg P ha^{-1} $year^{-1}$ when the animal density was reduced from 1.4 to 0.8 livestock units ha^{-1}.

The total content of P in mineral soils of a temperate climate is often 0.02–0.08%. The organic P fraction may constitute 25–65% of the total amount of P, and is important for the nutrition of plants (Schachtschabel et al., 1998). In general, Norwegian soils are slightly acidic and P is mainly absorbed to aluminium (Al)- and iron (Fe) oxides. P from organic sources such as FYM will be less readily adsorbed to soil than soluble mineral P fertiliser, as demonstrated by Øgaard (1996). Also, the soil microflora and -fauna will be more important in an organically managed system. An increased potential for mineralisation of organic P in an organically managed soil as compared to soil fertilised with inorganic P was found by Oberson et al. (1993). Further, they found more microbially-bound P and a more rapid cycling of P through the microbial biomass (Oberson et al., 2000) in the organically managed soil.

The general restrictions on nutrient inputs may gradually render organic livestock farming systems P deficient, as shown by P shortages in organic livestock systems, especially with low animal density. This will probably cause decreasing concentrations of plant-available P in soil, as found for 12 farms during conversion to organic farming by Løes and Øgaard (1997); and in field experiments e.g. by Oehl et al. (in press), Penfold et al. (1995) and Aasbø et al. (1999). With lower P concentrations in soil and low P inputs, the crops may gradually suffer from P deficiency. Crop plants may adapt to low-P soil by increasing root surface or increased root-induced solubilisation of soil P, or colonisation with mycorrhizal fungi (Gahoonia and Nielsen, 1998). Also, there is a potential for breeding P-efficient genotypes of crop species (e.g. Caradus, 1983; Gahoonia et al., 1997; Gahoonia et al., 1999; Nielsen and Barber, 1978). However, plant adaptation to low(er) P concentrations in soil and more rapid mineralisation of soil organic P may not be sufficient to ensure a satisfying yield level. Hence, it is of interest to study the long-term effects of organic management on soil P concentrations. As reviewed above, decreasing soil P concentrations with time has often been found in field experiments, but it is of interest to study if a similar decrease can be found in practice on farm level. Another aim of the paper is to evaluate the soil P levels after long-term organic management, and to assess the sustainability of organic dairy farming systems in their present state with respect to P.

Material and methods

Participating farms

On five organic dairy farms that had participated in previous soil investigations, a second set of samples were taken from all cultivated soil and analysed to study temporal changes in P concentrations. The farms are located in different regions of Norway (Table 1), and have been numbered 1, 2, 3, 4 and 5 by increasing period of organic management. The conversion year (defined as the first year no conventional fertilisers were used) for the farms was 1987, 1986, 1984, 1979 and 1932, respectively. Farm 1, 4 and 5 are biodynamically managed.

On farm 1, the bedrock consists of sandstone (sparagmite) with a low nutrient content, and the soils are glacifluvial deposits, mainly loamy sand and sandy loam with a low to medium content of organic matter in the topsoil, on average 18 g total carbon (C) kg^{-1} soil (level of organic matter in soil is characterised according to Sveistrup, 1984, assuming a content of 500 g total C per kg soil organic matter according to Schachtschabel et al., 1998). On farm 2, the bedrock is precambrian gneiss and granite and the soils are marine deposits with a varied texture from loamy sand to silty clay loam, and a medium content of organic matter in the topsoil, on average 26g kg^{-1} total C. On farm 3, the bedrock is shale and gneiss containing mica and the soils are fluvial deposits, mainly loamy sand with a medium content of organic matter in the topsoil, on average 21 g kg^{-1} total C. On farm 4, the bedrock is cambro-silurian shale and limestone and the soils are morainic deposits, mainly loam and clay loam with a high content of organic matter in the topsoil, on average 51 g kg^{-1} total C. On farm 5, the bedrock is precambrian gneiss and granite and the soils are marine deposits, partly loamy sand/sandy loam and partly silt loam with a medium content of organic matter in the topsoil, on average 28g C kg^{-1} soil.

The P-AL concentration is commonly reduced by increasing clay content, due to increased capacity to

Table 1. General information on the five organic dairy farms. Location, degrees N, E; Altitude in m above sea level (Alt), annual precipitation in mm (AP), acreage of cultivated farmland in ha (Land), average approximate number of milking cows (Cows); sampling years, 1989, 1998 etc; and number of soil samples at each sampling, (topsoil, subsoil) (n)

Farm	Location	Alt	AP	Land	Cows	Sampling years	n
1	61°40′N 11°10′E	333	485	8.0	8	1989, 1998	18, 3
2	60°10′N 11°50′E	170	709	7.5	10	1989, 1995	23, 8
3	63°40′N 08°55′E	30	1394	13.5	14	1990, 1998	27, 7
4	60°40′N 11°10′E	200	552	53.0	19	1989, 1997	82, 20
5	59°53′N 11°20′E	138	782	8.5	7	1985, 1997	6, 6

bind soil P in sparsely soluble forms by larger proportion of clay (Øgaard, 1994). However, the soil samples in our investigation were mainly light-textured soils. Only 23% of the samples had clay content between 25 and 40% (clay loam), and no samples contained above 39% clay. Hence, we have not differentiated between soil types in the presentation of results.

All farms have dairy production with average milk yields ranging from 3750 to 5200 kg cow^{-1} year^{-1} during the study period. These values are considerably lower than the average for conventional dairy farms in Norway (6304 kg in 1992). The crop rotations are mainly grass-clover leys and cereals; the leys are usually harvested for 3–4 years before ploughing and then re-established with barley as a cover crop. However, at farm 4 some crops are produced for sale, and the crop rotation lasts 10 years and includes 4 years of grain, 2 years of potatoes or vegetables and 4 years of grass-clover-alfalfa leys. The number of farms is not large enough to represent any average of Norwegian organic dairy farms, but they have in common that the farmers aim at self-sufficiency according to the organic standards and that all farms had been organically managed for at least 10 years at the second sampling.

Farm-level P balances

Farm-level P balances (kg P ha^{-1} year^{-1}) were calculated as the difference between the amounts of P in purchased and sold products, where P contents were set to standard values as collected by Ebbesvik (1997). P inputs from rainfall and dry deposits were negligible (Statens forurensningstilsyn, 1991, 1992), and were not included in the P balance. The P loss from runoff and drainage was not measured, but average total P losses from runoff and drainage in an organic dairy farming system on a morainic soil with 600 mm year^{-1} of precipitation were approximately 0.4 kg ha^{-1} year^{-1} (Eltun et al., 1996). Surface runoff through plant residues constituted the nearly half of these losses. We assume that comparable losses can be expected from the five farms in the present study, as the P-AL level in the soil and the amount of precipitation is comparable, with the exception of farm 3 with twice as much precipitation (Table 1) and a higher P-AL level (Table 2). Here, the P losses due to runoff and drainage may be somewhat larger.

For farms 1 and 3, the P balances were calculated from farm accounts for three years and for farm 2 for five years, starting with the year of the first sampling. For farm 4, the nutrient balance was very complicated due to the diverse production, and hence calculated from farm accounts for the year of the first sampling only. Generally, there have been small changes in the farming systems on farms 1–4 and the initial values have been used as representative for the whole period from the first to the second sampling. For farm 5, the

Table 2. Average P-AL concentrations, mg P kg, in topsoil (0–20 cm) and subsoil (20–40 cm) at the first and second sampling on five organic dairy farms compared to average P-AL values from topsoil on conventional livestock farms with the same main mineral soil texture in the same district (subsoil data not available). For the differences in P-AL between the first and second sampling as assessed by paired comparisons t-test, the level of significance is denoted as ns (not significant), * for $P<0.05$, ** for $P<0.01$, *** for $P<0.001$

Farm no.	Soil layer	P-AL at the 1st sampling	P-AL at the 2nd sampling	P-AL in conv. soil	Number of conv. samples
		mg P kg^{-1}	mg P kg^{-1}	mg P kg^{-1}	
1	Topsoil	91	75*	95	183
	Subsoil	21	62^{ns}		
2	Topsoil	57	50*	101	215
	Subsoil	15	25**		
3	Topsoil	140	119**	159	1085
	Subsoil	86	50^{ns}		
4	Topsoil	73	65***	100	474
	Subsoil	30	33^{ns}		
5	Topsoil	57[1)]	45*[1)]	114	595
	Subsoil	34[1)]	38^{ns} [1)]		

[1)] Determined by a colorimetric method, whereas all other values were determined by ICP. The average P-AL values for farm 5 measured by ICP were 64 (topsoil) and 56 (subsoil) mg P kg^{-1} at the second sampling.

P balance was based on the farmer's personal records, and the farming system was subject to larger changes. The P balance for the first part of the period, 1985–1994 was assumed to be equal to calculations made by Løes and Øgaard (1986). In 1995, 13 ha was rented from another organic farm and the herd increased from 8 to 11 cows. In the P balance, FYM used on the rented land was treated as sale and fodder produced there as purchase for the last part of the period. Farms 1 and 5 have purchased somewhat more fodder than the other farms, due to harsh climatic conditions on farm 1 and a higher livestock density on farm 5, as this farm also feeds two working horses.

Soil sampling and analysis

On each farm, topsoil (0–20 cm) and subsoil (20–40 cm) were sampled twice. The time span between the first and second sampling varied from 6 to 12 years (Table 1). Normally, the sampling occurred in late autumn after the final harvest, but for farm 3 in spring before fertilising on both sampling dates and for farm 5, in spring at the first and autunm at the second sampling. However, as the sampling season has been shown not to influence extractable soil P concentrations notably (Semb, 1966), we assume that the average P concentrations were not influenced by sampling season.

On farms 1, 2, 3 and 4, samples were taken from all cultivated fields, as composites of 10–12 soil cores taken within 5 m distance from a sample point described on a map to ensure that the sample points were the same on both sampling dates. The sampling density was approximately 2 samples ha^{-1} for topsoil, and 1 sample per 2 ha for subsoil. For sampling of subsoil, 0–40 cm soil cores were divided in 0–20 and 20–40 cm horizons. For farm 5, the sampling procedure was somewhat different, as the samples were composites of 10–12 soil cores taken from the 6 largest fields on the farm. At the second sampling, this composite sampling procedure was compared to the sampling procedure described for farms 1–4. The sampling procedure did not influence the average soil P-AL concentrations notably, as the average topsoil value by the sampling procedure described above (19 topsoil samples) was 66 mg P kg^{-1} (ICP values, see below) as compared to 64 for the 6 composite samples. In subsoil, the values were identical by both sampling procedures.

We believe that the influence of the crop yield and fertiliser level in the sampling year on the mean P-AL value is rather small as compared to the influence of the long-term crop rotation and fertiliser management, because the crop rotations in general did not change much from the first to the second sampling, the farm land in general was quite evenly and regularly fertilised and all fields were sampled at both sampling occasions.

In total, 156 (Table 1) topsoil and 44 subsoil samples were analysed for soil P extractable with 0.1 M ammonium lactate and 0.4 M acetic acid, pH 3.75, abbreviated P-AL (Egner et al., 1960). P-AL was chosen because it is in common use in Norwegian agriculture, and has shown a satisfactory relationship to response to P fertiliser under Norwegian conditions (Lunnan and Haugen, 1993). In addition, soil pH was measured in a soil-water suspension (1:2.5 v/v), and total C was determined in all samples with a Perkin Elmer 2400 analyser. As the content of calcium carbonate is generally low in Norwegian soils, the concentration of total C is equal to the organic C concentration. P-AL, pH and total C was analysed by the Agricultural Service Laboratory of the Norwegian Centre for Soil and Environmental Research, Ås.

P concentration in the AL-extract was measured by ICP (Inductive Coupled Plasma analysis), except from the first P measurement at farm 5, which was based on a colorimetric method. At the second sampling on farm 5, P-AL was analysed both colorimetrically and with ICP. The colorimetric method assesses only the amount of inorganic orthophosphate in the solution (Murphy and Riley, 1962), whereas the JCP procedure measures all P dissolved by the AL extraction. Therefore, ICP readings usually give 10–20% higher values than colorimetric readings (Krogstad, personal communication*). P-AL concentrations are presented as mg kg^{-1} dry soil, and are characterised as low (0–25 mg P kg^{-1}), medium (26–65 mg P kg^{-1}), high (66–150 mg P kg^{-1}) or very high (>150 mg P kg^{-1}).

In soil samples from farm 1, inorganic P was determined after extraction with 12 N sulphuric acid, and total P after heating by 550 °C for one hour to destroy soil organic matter, followed by extraction with sulphuric acid (Møberg and Petersen, 1982). Organic P was calculated as the difference between total and inorganic P. Total and inorganic P was analysed at the Department of Soil and Water Sciences, Agricultural University of Norway, Ås.

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Comparable data from conventional farms

To compare the P-AL concentrations on the organically managed farms to conventional farming systems, a set of average P-AL values was calculated from the database of the Norwegian Centre for Soil and Environmental Research. The number of soil samples included in the average value for each farm varied from 183 to 1085 (Table 2), and were taken from livestock farms in the same district as the respective organic farm. The results were from the period 1992–1999. Only soil samples with the same mineral soil texture as the main soil type on the organic farm were included.

Additional study

As an additional study, sets of 3 topsoil (0–20 cm) samples collected in 1995 from farms 4 and 5 and their respective conventional neighbour farms, altogether 12 samples, were analysed for P-AL, organic and total P and total C as described above. The samples were taken close to each other along the boundary between the farms.

Statistical analysis

To test to which extent changes in soil P concentrations with time were statistically significant, we compared the results from the first sampling to the results from the second sampling by paired comparisons two-sided *t*-test, PROC MEANS (SAS Institute, 1987). In the analysis, the pairs of samples were grouped as topsoil and subsoil samples from each farm.

Results and discussion

Farm and field level P balances

On average, the farm level P balances for farms 1 to 5, respectively, were 7, 1, 2, –3 and 12 kg P ha^{-1} $year^{-1}$ in the period from the first to the second soil sampling. These results reflect that the farms 1, 2, 3 and 5 are not self-sufficient with fodder, whereas on farm 4 there is a negligible amount of purchased fodder, and sales of plant products in addition to milk and meat. For farms 1, 2 and 3, the surplus is comparable to former results as published by Kerner (1993) and Kristensen and Halberg (1995). For farm 4 there is a P shortage even on the farm level. For farm 5 the P surplus is comparable to conventional Norwegian dairy farms (Gool,

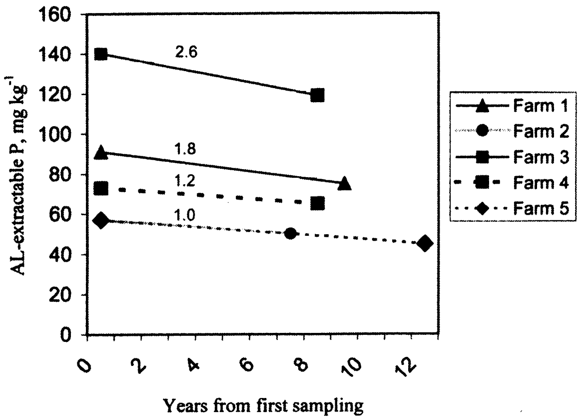

Figure 1. Decrease in average P-AL concentrations in the topsoil (0–20 cm) from the first to the second sampling on five organic dairy farms. The number of years between the first and second sampling varied, but the first sampling year has been put to 0. The period of organic management (whole farm converted) before the first soil sampling varied from 2 years on farm 1 to 53 years on farm 5. Rates of decrease are shown as small numbers above the lines.

1996). As shown by Nolte and Werner (1994) and Fagerberg et al. (1996), field level P balances are 2–3 kg P ha^{-1} $year^{-1}$ below farm level balances. These studies did not include P losses by runoff and drainage, which means that the shortage should be increased, or surplus decreased, by approximately 0.4 kg P ha^{-1} $year^{-1}$ for farms 1, 2, 4 and 5 and somewhat more for farm 3 (see 'Material and methods'). Hence, we believe that the average field level P balance is negative for farms 2, 3 and 4. For farm 1 there may on average have been a small surplus of P on the field level, and for farm 5 a larger surplus.

P-AL concentrations in soil

The average topsoil P-AL concentration decreased on all farms (Figure 1, Table 2), but was still medium or high at the second sampling. The decrease proceeded more rapidly when the initial P-AL levels were high, as shown by the steeper lines for farm 3 and 1 than for farm 2, 4 and 5 in Figure 1. This result is in accordance with Barber (1979).

When the pairs of soil samples from all farms were sorted according to the P-AL level at the first sampling, and divided into pairs of samples with initial low, medium, high and very high P-AL concentrations, no change occurred in topsoil with medium levels (Table 3). With high and very high initial P-AL concentrations in topsoil, a significant decrease occurred. The decrease was almost three times greater with very high than high initial P-AL level. Only three topsoil samples had a low P-AL concentration at the first sampling, but there was a tendency for increasing P-AL concentration in this group. In the subsoil, an increase in the average P-AL concentration was found in soils with low initial levels. In a study of farms in conversion to organic farming, Løes and Øgaard (1997) found a similar pattern, and a rapid decrease with very high initial levels also compares well to Aasbø et al. (1999), where the topsoil P-AL concentration decreased from 190 to 146 mg P kg^{-1} after only 7 years of self-sufficient organic dairy farming.

The subsoil P-AL concentrations were generally well below the topsoil values, and did only change on farm 2 where the average subsoil P-AL level was low at the first sampling. The P-AL concentration increased from 15 to 25 mg P kg^{-1} (Table 2), and hence the rate of increase (1.7 mg P-AL kg^{-1} $year^{-1}$) was larger than the rate of topsoil decrease on this farm (Figure 1). Also on farm 1 the average subsoil P-AL concentration was low at the first sampling and there was a tendency of increase, but there were only three pairs of subsoil samples from this farm. Increasing P concentrations in subsoil with initial low P concentration, and a parallel decrease in topsoil with initial medium or high P concentration, is in accordance with Alföldi et al. (1993). In that study, an increase in subsoil and decrease in topsoil P concentrations with time by organic livestock farming was found in a field experiment with initial very low P-AL concentration in the subsoil, and low to medium topsoil P concentrations.

Changes in P-AL concentrations in relation to P balances

The decrease in topsoil P-AL concentration on farms 2, 3 and 4 fits well with our assumption that the average field level P balance is negative. However, a similar decrease was found also for farm 1 and 5, where we assumed P surplus on field level. This may be due to inaccuracy in the P balances on farm level due to uncertainty in amounts of inputs and outputs as well as their P content, and/or on field level due to larger internal losses than assumed. On farm 5, the initial level was medium, 57 mg P kg^{-1}, and an average P surplus of 12 kg P ha^{-1} $year^{-1}$ on farm level should have caused an increase in P-AL concentration. However, this surplus was 14 kg P ha^{-1} $year^{-1}$ in the period 1985 to 1994, and was reduced to 5 kg in the period 1995 to 1997 when a large portion of the

Table 3. Average P-AL concentrations, mg P kg^{-1} dry soil, in topsoil (0–20 cm) and subsoil (20–40 cm) for 200 pairs of soil samples from long-term organic farms, divided into classes (see 'Material and methods') according to the P-AL level at the first soil sampling. Change = P-AL value at 2nd sampling minus value at 1st sampling. Level of significance is denoted as ns (not significant) (∗) for $P<0.1$, ∗ for $P<0.05$, ** for $P<0.01$, *** for $P<0.001$. The number of soil samples in each class, n is shown in italics

P-AL class at 1st sampling	Low	Medium	High	Very high
Topsoil				
P-AL at 1st sampling	20.9	46.8	100.2	188.4
P-AL at 2nd sampling	23.4	44.7	87.1	150.8
Change	2.5(*)	-2.1^{ns}	−13.1***	−37.6**
n	*3*	*74*	*61*	*18*
Subsoil				
P-AL at 1st sampling	15.4	36.6	91.6	
P-AL at 2nd sampling	26.9	42.8	65.6	
Change	11.5**	6.2^{ns}	-26.1^{ns}	
n	*19*	*18*	*7*	*0*

FYM was used on a rented land. This reduction in surplus during three growing seasons before the second soil sampling may have contributed to the decrease in topsoil P-AL concentration on this farm. Another possible explanation for decreasing P-AL concentrations in spite of a positive P balance is absorption of P to non-extractable forms in Al and Fe oxides in soil.

In some studies, decreasing concentrations of topsoil extractable P have been found on experimental fields with an initial medium or high P concentration, 6–11 years after these were converted to organic livestock farming (Alföldi et al., 1993; Løes et al.,1998 and Penfold et al., 1995). This compares well to the decreases in topsoil P-AL concentration found during a period of 9, 6 and 8 years, respectively, on farms 1, 2 and 3 where the conversion to organic farming occurred 2, 3 and 6 years, respectively, before the first soil sampling. By longer period of organic management, we assumed that the P-AL concentrations would stabilise. However, decreasing topsoil P-AL concentrations were also found on farm 4 and 5 with 10 and 53 years of organic management, respectively, before the first sampling. The reason for the decrease on farm 5 was probably the reduced P surplus on farm level shortly before the second soil sampling as described above. On farm 4, the decrease compares well to results found by Oehl et al. (in press) in a long-term field experiment on organic livestock farming in Switzerland. In this study, decreasing concentrations of plant-available P were found after 14, and again after 21 years. Such results reflect that it may take many years of organic management before the concentration of plant-available P in soil has decreased to a stable level, even by an initially only medium high level.

The P-AL level on farm 5 (Table 2) is not comparable with the level on the other farms, due to different methods of measuring the P concentration in the AL-extract at the first sampling (see 'Material and methods'). However, when measured by ICP the P concentration in the AL-extract of the soil from farm 5 by the second sampling was at the same level as on farm 1, 2 and 4 (Table 2).

This means that the farm with the longest time period of organic management still has a P-AL concentration comparable to farms with a much shorter period of organic management, but the explanation for this is probably the average larger P surplus on farm level.

Total and organic P concentrations in soil

To study if the concentrations of total and organic P changed with time, these concentrations were measured in soil samples from farm 1. The average level of total P in 1998 was 535 mg P kg in topsoil (range 383–729) and 503 in subsoil (range 421–597), with no statistically significant changes in topsoil nor in subsoil from the first to the second sampling. For organic

Table 4. Average topsoil (0–20 cm) concentrations of P-AL, organic P and total P and total C (mg kg^{-1} air-dry soil) in sets of 3 soil samples from two organic farms (Org 4, Org 5) and two conventional neighbour farms (Con 4, Con 5). Sampling year 1995. Within each pair (Org, Con), values with different letters are statistically different at the 5% level of significance

Parameter	Org4	Con4	Org5	Con5
P-AL	65a	54a	46x	62y
Organic P	619a	558a	722x	611y
Total P	1498a	1371a	1310x	1228x
Total C	51a	52a	31x	26y

P, there was an increase from 108 to 121 mg P kg in topsoil (*P*= 0.03). In subsoil, there was a tendency of increase, on average, from 46 to 92 mg P kg^{-1}, but as only three pairs of samples were available this result is uncertain. We considered these results as too inconclusive to justify analysing all soil samples for total and organic P. The P shortages or surpluses were probably too small, and the time span between the first and second sampling too narrow, at least for farm 2, to find reliable changes in total and organic P.

Effects of long-term organic management

As farm 5 has been managed organically for a much longer time period than the others, the soil P dynamics might be somewhat different here than on the other farms. Our results indicate higher topsoil content of organic matter, a deep topsoil layer as well as more easily soluble organic P on this farm, which will be discussed below.

Higher concentrations of organic P and total C in topsoil on farm 5 as compared to a conventional neighbour farm was found in the additional study of farm 4 and 5 and their respective conventional neighbour farms (Table 4). The P-AL concentration was lower on farm 5 than on the conventional neighbour farm. On farm 4, there were no statistically significant differences in soil P or C concentrations as compared to the conventional neighbour farm, but the results from farm 5 compare well with the results of Reganold et al. (1993). In this study, higher content of C, but less extractable P in soil was found after up to 18 years of organic management in a comparison of organic and conventional neighbour farms in New Zealand. The reason why no differences in total C and organic P concentrations were found for farm 4, where the management had been organic for 16 years when the study was performed, may be a general high content of soil organic matter in the area where both farms are located.

There was a small difference between topsoil and subsoil P-AL values on farm 5 as compared to the other farms (Table 2), and the subsoil values were remarkably large, on average 56 mg P kg^{-1} dry soil, varying from 44 to 74 (measured by ICP). Also, there is a small difference between top- and subsoil organic matter content on this farm, as the average values are 28 mg total C kg^{-1} in topsoil and 22 mg in subsoil. Hence, the topsoil thickness here on average is larger than 0–20 cm. For practical purpose, the topsoil thickness was not measured in the present study, but defined as the 0–20 cm layer. For most farms, this simplification did not hamper the results, but for farm 5 the term 'subsoil' does not fit the 20–40 cm layer. Increased thickness of the topsoil layer by long-term organic farming was also found by Pettersson and Wistinghausen (1981) and Reganold et al. (1993). Oehl et al. (in press) found increasing levels of total P in subsoil, which could explain why the P decrease in topsoil was larger than expected from the P shortage on field level. The increasing P-AL concentrations in subsoil with initial low P-AL level found on farm 2 is also an indication of downwards transport of P. A reasonable explanation for this may be earthworm activity. Pettersson and Wistinghausen (1981) and Pfiffner et al. (1993) found more earthworms in organically than in conventionally managed soil, and Hansen and Engelstad (1999) found much larger earthworm populations by low soil compaction in an organic farming system. Low compaction has in fact been achieved by using working horses and small tractors on farm 5. By forming tubes through the soil, earthworms mix soil from different layers. Graff (1970) found that the material lining fresh earthworm tubes at 25–50 cm depth contained 263 mg extractable P kg as compared to 57 mg P kg^{-1} in the bulk soil. In the topsoil (0–20 cm) the bulk soil contained 117mg P kg^{-1}.

On farm 5 the P-AL concentration measured by ICP was 24–39% above the colorimetric results, which is a much larger difference than was observed earlier for Norwegian soil samples (Krogstad, personal communication). The extracted P-AL in the soil samples from farm 5 that is not inorganic orthophosphate is probably some kind of organic P and indicates a relatively high level of easily soluble organic P in the soil at farm 5. This result may well be due to high biological activity in soil, as Oberson et al. (1993) found larger biological activity in the organically managed systems in a long-term field experiment and thereby a larger potential for mineralisation of soil organic P.

P-AL concentrations in relation to pH and total C

On farm 1 the soil was limed between the first and second sampling, and the topsoil pH increased from 5.8 to 6.3 ($P<0.001$). On farms 2, 3 and 4 the average pH levels decreased from 5.9 to 5.7, from 6.3 to 6.0 and from 6.5 to 6.3, respectively ($P<0.001$). Small, if any, amounts of lime were used on these farms between the first and second soil sampling. On farm 5, the topsoil pH was stable at 6.3, which seems somewhat surprising as no liming occurred between the first and second sampling, the crop rotations were comparable and the acidifying effect of acid precipitation was not lower than for the other farms (Tørseth and Semb, 1995). The subsoil pH values generally did not deviate much from the topsoil values, and a significant change in subsoil pH occurred only at farm 5, where this value increased from 5.9 to 6.2 ($P<0.01$). In summary, topsoil pH increased from the first to the second sampling on farm 1 (due to liming), decreased on farm 2, 3 and 4 and was unchanged on farm 5. It is well known that soil pH influences the availability of P (Schachtschabel et al., 1998), but whether change of pH has influenced the results in this study is not clear as the average topsoil P-AL concentrations were reduced both with increased, with reduced and without any change in soil pH. Most probably, the P balances have influenced the average soil P-AL concentration more than changes in soil pH.

For farms 2, 3 and 4 there was a positive correlation between P-AL and total C concentration in the topsoil at the second sampling. Pearson's correlation coefficient, r, was 0.36, 0.51 and 0.32, respectively. This result shows the importance of soil organic matter with respect to plant P nutrition, as organic matter retard P absorption and deliver P by mineralisation. Semb and Uhlen (1956) have also demonstrated the importance of soil organic P in an investigation of several field experiments. These authors concluded that soil organic P contributes significantly to the P nutrition of plants in soil with pH (H_2O) > 5.5 so that 1.5–2% of the organic P should be added to the extractable P concentration to assess the P-supplying ability of the soil.

P-AL concentrations on organic farms as compared to conventional

The average topsoil P-AL values were 50–80% of the level on comparable conventional farms (Table 2). This compares well to the results of two studies comparing conventionally and organically managed farms in the Corn Belt, US (Lockeretz et al., 1980) and on New Zealand (Reganold et al., 1993). In the Corn Belt, the average level of extractable P on organic farms was 75% of the level on conventional farms; 25.2 as compared to 33.8 mg P kg^{-1} by Bray l-P ($P<0.1$). On the New Zealand farms, the level of extractable P on the organic farms was 70% of the conventional level; 45.7 as compared to 66.2 mg P kg^{-1} ($P<0.01$). For less easily extractable P (Bray 2-P), there was no difference in P concentrations between the farming systems in the Corn Belt study, and in the New Zealand study, no difference in total P was found between the groups of farms.

Assessment of sustainability

A P-AL concentration of about 70 mg P kg^{-1} is regarded as optimal with regard to both yield level and a sufficiently low risk of stimulating algae-growth by soil erosion to water bodies (Krogstad and Løvstad, 1987). Hence, the average P-AL levels of the organic farms are closer to optimal than the comparable conventional P-AL levels (Table 2). However, soils with medium to low level of P-AL are dependent on regular P additions to give satisfactory yields. In an investigation of several Norwegian field trials, P-AL values below 30 mg P kg^{-1} gave considerably reduced yields of grass when no P-fertiliser was used and P additions almost doubled the average yield. The yield level was approx. 2.8 tonnes dry matter (DM) ha^{-1} by no P addition, and 5.2 tonnes DM ha^{-1} by 20 kg P ha^{-1} $year^{-1}$ (Lunnan and Haugen, 1993). In fields with soil P-AL concentrations above 100 mg P kg^{-1} no yield increase was obtained with P addition, and in fields with P-AL concentrations between 30 and 100 mg P kg^{-1} the average yield level increased only from 6.5 to 7.1 tonnes DM ha^{-1} by a P addition of 20 kg ha^{-1} $year^{-1}$. From this study, we may conclude that a P-AL concentration of about 30 is a critical level, which is also reflected by the limit between low and medium level, 25 mg P kg^{-1}.

Some long-term field experiments in Norway have shown that the P-AL concentrations may stabilise on a level between 30 and 50 mg P kg^{-1} by a P balance close to zero. In a study on morainic soil, the initial P-AL level is not known but after 60 years, a P surplus of 10 kg P ha^{-1} $year^{-1}$ had given a P-AL concentration of 45 mg P kg^{-1} whereas the P-AL concentration was 30 mg by a zero P balance (Ekeberg and Riley 1995). In a study lasting 21 years on clay soils, the initial P-AL concentration in a soil with 36% clay kept stable at approximately 35 mg P kg^{-1} by a zero P balance, and in a soil with 25% clay the initial P-AL concentration kept stable at 50 mg P kg^{-1} even by a small average shortage of −4 kg P ha^{-1} $year^{-1}$ (Øgaard, 1995). In the present study, the average topsoil P-AL level had not stabilised and the level was above 50 mg P kg^{-1} for all farms (ICP value for farm 5). However, the decrease has occurred mostly in samples with initial high and very high P-AL concentrations, as we found no statistically significant change in topsoil P-AL for samples with an initial medium level (25–65 mg P kg^{-1}) (Table 3). Hence, it is well possible that the average P-AL concentration will stabilise on a medium level on the farms, but this level has not yet been reached. An argument against this is that the number of topsoil samples with low P-AL concentrations doubled from the first to the second sampling, even if this regards only a minor part of the topsoil samples. 3 samples had <25 mg P kg^{-1} by the first sampling (1 sample on farm 2, and 2 on farm 4), and 6 samples by the second sampling (1 sample on farm 1, 4 on farm 2 and 1 on farm 4).

The relation between rate of decrease and P-AL level (Figure 1) gives some indication of how long the farm management may proceed with the present nutrient balances to reach an average optimal (70 mg P kg^{-1}) or critical (30 mg P kg^{-1}) state. On farm 3, where the average topsoil P-AL was almost at the very high level at the first sampling, the rate of decrease was 2.6 mg P kg^{-1} $year^{-1}$, and on farm 1 with a high but lower level than on farm 3, the decrease was 1.8 mg P kg^{-1} $year^{-1}$. On farm 2, 4 and 5 with medium or high but only slightly above medium levels at the first sampling, the rate was only 1 or 1.2 mg P kg^{-1} $year^{-1}$. If, for simplification, we assume that the decrease in P-AL values proceeds with a linear average rate of 1.8, farm 3 may be managed without any changes in the P supply for 27 years before the optimal level of 70 mg P kg^{-1} is reached. This will probably be the most sustainable way to handle the P reserves in the soil on this farm. For the other farms, the farmer should be aware of the situation as the average P-AL values at the second sampling were close to, or below 70 mg P kg^{-1}. If the decrease in P-AL values proceeds at 1.0 mg P kg^{-1} $year^{-1}$ on farms 2, 3, 4 and 5, the critical level of 30 mg P kg^{-1} will be reached within 15–45 years. Cultivated soil should not be depleted below this value because this will cause serious yield decreases as shown above. The farmers that have participated in this study have not reported on P deficiency symptoms, but they should monitor soil P concentrations regularly and take good care of soil and manure P resources. On all farms that had an average medium, or high but close to medium level at the second sampling, some kind of P will probably have to be supplied from external sources within 20–40 years.

Conclusion

Case studies on five Norwegian dairy farms showed decreasing concentrations of plant available P (P-AL) in the topsoil after long-term organic farming. However, the average P-AL level was still medium or high, which suggests that the P-AL concentrations are sufficient for crop production as long as somewhat more P than the crop removes is added in fertiliser. Farmers managing their soil organically should therefore monitor soil P concentrations regularly, and increase the P fertilisation on the fields where P-AL concentrations approach critical values. There is, however, a need for research to assess which levels of soil P concentrations are optimum for organic management, as well as research on how to produce P fertilisers that fit into the aims and regulations for organic farming. The results found on farm level in the present study confirms the results from several field experiments on organic livestock farming. Hence, for studies of soil P concentrations and P balances, results from field experiments may be very valuable for practical purpose.

The farm level case studies as well as previous studies of organic farming systems indicate a larger topsoil volume accessible for root growth, transport of P from topsoil to subsoil and enhanced solubility of organic P by long-term organic farming. Such results show that soil P dynamics differ according to farming practice and fertiliser amendments, and this deserves closer observation.

Acknowledgements

We want to express our grateful thanks to the farmers, who gave us access to their farms as well as friendly co-operation. Also, thanks to Willie Lockeretz for valuable comments on the manuscript.

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