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Phosphorus accumulation and spatial distribution in agricultural soils in Denmark

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ABSTRACT

Over the past century phosphorus (P) has accumulated in Danish agricultural soils. We examined the soil P content and the degree of P saturation in acid oxalate (DPS) in 337 agricultural soil profiles and 32 soil profiles from deciduous forests sampled at 0–0.25, 0.25–0.50, 0.50–0.75 and 0.75–1.00 m in the nationwide 7 km Grid System in Denmark. Changes in soil P content between 1987 and 1998 at 0–0.25 and 0.25–0.50 m were also examined in 337 and 335 agricultural soil profiles, respectively. Compared to forest soils, the agricultural soils contained more total P down to 0.75 m depth (264 mg P kg^{-1}, or 88% more at 0–0.25 m depth, 191 mg P kg^{-1} or 82% more at 0.25–0.50 m depth and 120 mg P kg^{-1} or 63% more at 0.50–0.75 m depth). The mean degrees of phosphorus saturation (DPS) of the agricultural soils were 32, 23 and 15% in the three upper soil layers, which were approximately twice as high as at the corresponding depths of deciduous forest soils. Between 1987 and 1998 total soil P content in the agricultural soils increased at both 0–0.25 and 0.25–0.50 m depth. On average, the increase corresponded to an annual accumulation of *c.* 25 kg P ha^{-1}, with the increase fairly equally divided between the two soil layers. The accumulation corresponds with the national P surplus of *c.* 20 kg P ha^{-1} calculated from national statistics. This investigation shows that long-term surplus P fertilisation of agricultural soils has resulted in P accumulation to at least 0.75 m depth. The paper discusses the potential importance of leaching, deep tillage, erosion and bioturbation for the observed accumulation of P in the subsoil.

1. Introduction

The agricultural phosphorus (P) load has become the major contributor to the eutrophication of many Danish lakes and estuaries, as P emissions from other sources, e.g. sewage and rural dwellings, have declined dramatically following the implementation of environmental regulation (Kronvang et al., 2005a). In order for Denmark to comply with the goals of the EU Water Framework Directive (European Union, 2000) for good ecological quality in surface waters, a substantial reduction of the current agricultural P load to the aquatic environment is required (Kronvang et al., 2005b).

In many intensively cultivated areas in Western Europe or North America, P fertilisation has for decades exceeded the removal of P in harvested products (e.g. Kronvang et al., 2009), resulting in accumulation of P in soil. This is also the case in Denmark, where excess P has been added with manure or fertilisers for many years (Kyllingsbæk, 2008; Maguire et al., 2009). A main source of today's agricultural P loss is therefore the accumulated soil P, posing a long-term risk for P losses to surface waters. At the landscape scale the distribution of accumulated soil P is predominantly determined by the structure (type and size of farms, management practice, fertiliser input, animal density, etc.) and the structural development in agriculture over time. Worldwide, soil P accumulation is typically related to intensive livestock production (Kronvang et al., 2009). Phosphorus is also a limited resource, and the global demand for P fertilisers, recycling of P and improved P use efficiency in agriculture is expected to increase substantially in the years to come (Cordell et al., 2009, 2011) and accumulated soil P therefore represents an important resource for future crop production (Schröder et al., 2011). Agriculture consequently faces the challenge of devising management strategies that both limit P losses to surface waters and secure the optimal utilisation of soil P. The success of such management strategies will depend on where in the landscape P has accumulated, how P is distributed in the soil profiles and how readily P is released to run-off and to the growing crop.

Phosphorus is often unevenly distributed in the soil profile, mainly accumulating in the A-horizon (Anderson, 1980). In agricultural soils, the application of surplus P in animal manure or other products enhance the P enrichment of the topsoil even further. Linkages between surplus P additions and P accumulation in deeper soil layers have previously been documented, for example in selected soil profiles from long-term field experiments under different agricultural management systems (e.g. Garz et al., 2000; Oehl et al., 2002; Stephenson

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and Chapman, 1931; Watson and Matthews, 2008). However, to our knowledge, there is no published work on the effect of agricultural management on P accumulation in soil on a larger scale across several soil types and soil depths. We therefore performed an inventory of the P status of soils across Denmark that had been collected on the "national soil sampling scheme for monitoring nitrate" (in Danish: KVADRATNETTET). KVADRATNETTET is a regular 7 × 7 km grid across Denmark, where soils have been sampled annually at different depths in subsets of the grid points since 1987. Our objective was to study P accumulation and its dependence on soil texture and P application either as inorganic fertiliser or in animal manure. Specifically, our aims were (*i*) to compare agricultural with deciduous forest soils for total P content and the degree of phosphorus saturation (DPS) (van der Zee et al., 1990) and (*ii*) to investigate the P status in different soil textural classes and changes in P status at different depths in agricultural soil profiles for the period 1987 to 1998.

2. Materials and methods

2.1. Danish agriculture, present and past

In 1998, two thirds of the land area in Denmark was cultivated (www.statistiken.dk). Some parts of the country have been intensively farmed since about 1100 A.D. when villages were established, while in other areas, particularly on lowland and coarse sandy heathland soils, arable farming only started during the 19th century. Hence, the agricultural redistribution of nutrients has taken place with considerable geographic variation for a very long time. In recent decades, nutrient balances have been changing at an accelerated pace in response to the introduction of novel techniques, markets or regulations. The trend towards more specialised farms has increasingly affected geographic differences in animal densities and, hence, nutrient loads and distribution. Intensive livestock production dominated by pigs and dairy cattle prevails in the western parts of the country, while arable farming characterises the eastern parts (Dalgaard et al., 2009). Also at a finer geographical scale, i.e. historically at village level and in more recent times at farm level, the distribution of animal manure has been heterogeneous, as fields further away from the village or farm typically have received less animal manure than fields closer by (Farbech et al., 2002).

In Denmark, the addition of mineral P fertilisers started around the year 1900 and generally accelerated until the beginning of the 1980s (Kyllingsbæk, 2008). Since then the national annual P surplus has declined from around 30 kg P ha^{-1} to 13 kg P ha^{-1} in 2000. This fall arose from a reduction in the use of inorganic P fertilisers during this period, while animal production increased and P removal with plant products was almost constant. (Kyllingsbæk, 2008; Kyllingsbæk and Hansen, 2007). This recent decline in P surplus is mainly a result of regulation, which has been implemented through successive national action plans since 1987 to reduce nutrient losses to the aquatic environment (Heckrath et al., 2008; Kronvang et al., 2008; Maguire et al., 2009). These regulatory measures included: (1) compulsory nitrogen-based management of animal manures (2) standards for how much N can be applied to each crop depending on potential yield and (3) restrictions on livestock densities on farmland ranging from 1.7 Livestock Units (LSU) ha^{-1} for pig manure to 2.3 LSU ha^{-1} for cattle manure (in 1994 the national definition of 1 LSU was set to correspond to 108 kg N yr^{-1} applied to the field).

2.2. The national soil sampling grid

The 7-km sampling grid was established in 1987 by the Knowledge Centre for Agriculture to systematically monitor soil inorganic N content across Denmark. The grid is permanent and subsets of the grid points are selected and sampled annually for monitoring soil inorganic N content. There were originally 830 grid points in total, of which 590 were situated on agricultural land, 32 on deciduous forested land and 208 on other land use types (e.g. coniferous forest, scrub, heathland, grassland, and marshland). Each grid point represents a sampling area measuring 50 × 50 m. Information on land use has been registered annually for the sampled agricultural grid points including the type and amount of fertiliser, crop type, handling of crop residues, etc. Soil samples are collected to 1 m depth in 0.25 m increments, typically in January–February. Each sample is a composite of 16 soil cores of 0.025 m diameter taken randomly within the sampling area. Soil material not used for nitrate analysis is air-dried, sieved to <2 mm and stored at room temperature in a soil archive. After the initial campaign in 1987, about half of the agricultural grid points have been sampled annually. For the purpose of our study, soils from additional grid points were sampled in 1998 and prepared in the same way. This yielded a set of 338 agricultural grid points sampled both in 1987 and 1998 (Fig. 1). We additionally analysed the 32 deciduous forest soils from 1987 (Table 1). For the remaining agricultural grid points there was either not enough soil material left for analysis from 1987 or sites had gone out of agricultural production by 1998.

Farm data on yields were incomplete, which prevented the calculation of P exports and hence P balances at each grid point. Based on the type and amount of fertiliser added to each grid point between 1987 and 1998, the data were grouped into grid points that had received no animal manure during the period (69 points), or had received animal manure corresponding to either >1 LSU (108 points), or <1 LSU (160 points). For this purpose, LSUs were calculated from records of the animal manure applications at each site. Here, we defined 1 LSU as 100 kg N y^{-1} applied to the field, which is slightly lower than the general definition of 1 LSU in Denmark at that time. More details about the selection of the grid points for this study are given by Heidmann et al. (2001).

2.3. Soil analyses

Soil texture was determined on all samples in 1987 (Gee and Bauder, 1986). Based on these analyses, the grid points were assigned to textural classes corresponding to the Danish soil classification system (Table 1, Landbrugsministeriet, 1976). Fig. 1 shows a soil type map of Denmark which is based on the same textural classes. The Weichsel glaciation has characteristically shaped the physical geography of Denmark and left moraine landscapes on glacial till in eastern Denmark including parts of the Jutland peninsula and a large glacial outwash plain in south-western Jutland. This explains the predominance of light-textured soils in the west and fine-textured soils in the east of the country. The most common soils types (FAO classification) are Podzols and Arenosols on well to moderately-drained sandy parent material, and Luvisols and Cambisols on well to moderately-drained loamy and clayey parent material (Breuning-Madsen et al., 1992).

Total P was determined by wet oxidation in a mixture of concentrated perchloric and sulphuric acid (Kafkafi, 1972). Bicarbonate extractable P (Olsen P, Olsen et al., 1954) was analysed according to Banderis et al. (1976). Oxalate extractable Al, Fe and P were determined by ICP-OES (Inductively Coupled Plasma Optical Emission Spectrometry) after extraction with acid ammonium oxalate (Schwertmann, 1964) and the degree of P saturation (DPS) was calculated as the ratio between the molar concentrations of P and half the sum of Al and Fe in soils (van der Zee et al., 1990). Total P (TP) and Olsen P were determined at all available grid points in the 0–0.25 m and 0.25–0.50 m layers of agricultural soils from 1987 and 1998. Total P was also analysed in the layers 0.5–0.75 m and 0.75–1.0 m of agricultural soils from 1998 and forest soils from 1987 (all depths) (Table 2). Oxalate extractable Al, Fe and P were analysed in three layers to 0.75 m depth in agricultural soils from 1998 and forest soils from 1987 (Table 3). Total P, oxalate extractable P and Olsen P analyses were done during 1999 and 2000