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Sammendrag

Innholdet av fosfor (P) i jorda kan avta over tid ved økologisk drift, hvis man ikke sørger for en tilstrekkelig tilførsel av næringsstoff fra kilder utenfor gården. En aktuell kilde til P-forsyning er struvitt (magnesium-ammonium fosfat). Struvitt er et mineral som felles ut når konsentrasjonen av disse næringsstoffene blir høy nok, for eksempel i et urinseparerende toalett. Struvitt kan produseres i kloakkrenseanlegg, og bidra til at vannet som slippes ut i resipienten inneholder mindre P. Hvis struvitt blir godkjent som et tillatt gjødselmiddel i EU, er det mulig at dette mineralet også kan bli tillatt brukt i økologisk dyrking.

Et renseanlegg ved Hamar, drevet av Hias IKS, har utviklet en patentert metode for biologisk rensing av avløpsvann, som muliggjør utvinning av struvitt fra renseanlegget. En prøve av struvitt fra Hias ble sendt til Tingvoll, hvor det ble brukt i et forsøksfelt med flerårig eng, kalt «SoilEffects». Dette

forsøksfeltet, som ble etablert i 2011, brukes til å undersøke effekten på jord og planter av at husdyrgjødsla på gården råtnes ut i et biogassanlegg før den spres på jorda. Vi sammenlikner vanlig kumøkk (bløtgjødsel) og utråtnet kumøkk, i lav og høy mengde (3 eller 6 tonn per daa og år). Vi har også et sett med forsøksruter uten gjødsling. Til sammen har vi åtte gjentak (forsøksruter) av hver behandling, og halvparten av rutene ble tilsatt struvitt rett før husdyrgjødsel ble spredd på forsøksfeltet i slutten av april 2018. Vi tilsatte en mengde som tilsvarte 4 kg P per daa. På forhånd hadde vi tatt ut jordprøver i to dyp, for å kunne se på effekten av å tilføre struvitt.

Engavlingene ble registrert i juni og august. Første slått var unormalt lav og preget av tørke, men ga en betydelig avlingsøkning ved tilførsel av struvitt der det ikke var tilført husdyrgjødsel, og ved tilførsel av lav mengde husdyrgjødsel. Andre slått ga bedre avlinger, og fortsatt et positivt utslag for struvitt i disse behandlingene. I gjennomsnitt var det 240 kg tørrstoff (TS) per daa i totalavling (sum av første og andre slått) uten noen tilførsel av gjødsel eller struvitt, og 410 kg med tilførsel av struvitt. I behandlingene som fikk lav mengde husdyrgjødsel var totalavlinga i gjennomsnitt 500 kg TS/daa uten struvitt, og 595 med struvitt. I behandlingene som fikk mye husdyrgjødsel var totalavlinga i gjennomsnitt 635 kg TS/daa uten struvitt, og 620 med struvitt. Struvitt økte fosforinnholdet i jord og planter.

Graset fra begge slåtter ble analysert for innhold av mineraler, og nye jordprøver ble tatt ut etter andre slått. Tilførsel av struvitt økte fosforinnholdet i enga, og innholdet av P i jorda målt som AL-løselig P. Struvitt økte også innholdet av magnesium i jord og planter. pH i jorda økte fra vår til høst etter tilførsel av husdyrgjødsel, men tilførsel av struvitt reduserte denne effekten. Vi målte også virkningen av struvitt på mengden av P i en løsning som lot seg binde til oksider av jern og aluminium i jorda (adsorbert P). Jorda inneholder en viss mengde med slike oksider, og tilførsel av P gjennom flere år i gjødsel, samt tilførsel av struvitt, kunne tenkes å redusere denne P-mengden. Det var imidlertid ingen sikre forskjeller mellom jord som hadde fått tilført lite eller mye husdyrgjødsel over flere år, og vi fant heller ikke noen sikker effekt på denne egenskapen av å tilføre struvitt.

Summary

The soil P concentration commonly declines over time by organic management, if the farm does not acquire enough fertilisers or other inputs containing P from outside. An interesting source to supply farms with P is struvite (magnesium-ammonium phosphate). This mineral easily precipitates when the concentrations of these nutrients is high enough, such as in a toilet separating urine. Struvite may be produced in a wastewater treatment plant, as a method to reduce the P concentration in the water reaching the recipient. If struvite is allowed as a mineral fertiliser in the general fertiliser regulation of the European Union, which is currently under revision, this mineral may be allowed also in certified organic agriculture.

A wastewater treatment plant in Hamar (south-eastern Norway), Hedmarken inter-municipal wastewater corporation (Hias IKS) has developed a patented method to precipitate struvite efficiently. A sample of struvite produced by this process at Hias was sent to Tingvoll (north-western Norway) to be tested in an experimental field with perennial ley, called “SoilEffects”. This

experiment, established in 2011, is used to study the effect on yields and soil characteristics when the slurry from the farm's herd of organic dairy cows is anaerobically digested to produce biogas before being applied as fertiliser. Non-digested and digested slurry are compared in two levels of manure application, low and high (30 or 60 tons of slurry per ha and year), and with a control with no manure application. Eight replicates are available of each treatment, and to half of these plots, struvite was applied shortly before the slurry was applied, in the end of April 2018. We applied an amount of struvite corresponding to 40 kg P per ha. Before the application, soil samples had been collected from two depths, to study the effect of struvite on soil characteristics.

Yields of ley were recorded in the two cuts, which occurred in June and August. The yield level at the 1st cut was generally low due to drought, but the increase in yield was significant with application of struvite in the plots receiving no manure, and with low manure application. At the 2nd cut, yield levels were generally higher, and again a positive effect of struvite was found in these treatments. On average, the total yield (sum of yields at the 1st and 2nd cut) was 2.4 tons of dry matter (DM) per ha with no application of manure or struvite, and 4.1 with application of struvite. In treatments receiving a low amount of manure, the mean total yield was 5 tons per ha with no struvite, and 6 tons with struvite application. In treatments receiving high amounts of manure, the mean total yield was 6.4 tons per ha without struvite, and 6.2 with struvite.

The concentrations of minerals in aboveground plant material from both cuts were analysed, and new soil samples collected after the 2nd cut of ley. Application of struvite increased the P concentrations in plant material and the concentration of AL-extractable P in soil. Struvite further increased the concentration of magnesium in plant material and soil. Soil pH increased from spring to autumn by application of manure, but the application of struvite reduced this effect. The amount of P being adsorbed to oxides of iron and aluminium in the experimental soil from a solution containing dissolved phosphate was also recorded. The soil has a certain amount of such oxides, and long-term application of P in manure, as well as application of P in struvite, could possibly reduce the amount of P being adsorbed from the solution. However, no significant differences were found between soils which had received low or high amounts of manure over several years, and we did not find any effect of struvite application on this characteristic in this soil.

COUNTRY:	Norway
COUNTY:	Møre and Romsdal
MUNICIPALITY:	Tingvoll
LOKALITET:	Tingvoll farm

APPROVED	PROJECT LEADER
Turid Strøm	Anne-Kristin Løes
NAME	NAME

Preface

P is a plant macronutrient of large importance and needs a careful management since reserves are scarce. The current P management in society is poor, since a significant amount of P gets lost because we do not recycle all available nutrients. This is a challenge also for organic agriculture. Research has shown that even in dairy farming systems with a relatively high import of nutrients in animal feeds, soil P concentrations decline over time. Research has also shown that low P concentrations in soil may be challenging to increase. Hence, there is a large interest in applicable recycled fertilizers among organic growers. Struvite is a fertilizer with interesting characteristics, which can fit well in organic farming systems to replace P exported off the farm in products.

So far, struvite has not been tested in field with organic growing conditions in Norway. By combining an established field experiment in perennial ley, and a test batch of struvite produced in a pilot plant at Hias IKS inter-municipal waste treatment corporation, we created a short-term project, economically supported by Møre and Romsdal county council and the Ministry of Agriculture and Food.

The project gave interesting results, which are presented in this report. Tatiana Rittl started her employment in NORSØK in 2019 and hence was not involved in the experimental design but wrote this report and made all diagrams and calculations. Professor Tore Krogstad (NMBU) contributed especially with the presentation of sorption data. Sondre Eikås, Hans Emil Glestad, Torgeir Saltnes and Gjermund Sørensen at Hias IKS contributed with struvite, welcomed us to visit the waste water treatment plant, explained the process and performed the chemical extractions required to measure adsorbed P. Anne-Kristin Løes initiated the SoilEffects experimental field, managed the struvite project and assisted Tatiana Rittl in the interpretation of results.

We highly appreciate the dedicated and thorough field work conducted by technicians in NIBIO and NORSØK; Anne de Boer, Hanne Iren Dahlen and Peggy Haugnes.

Tingvoll, 05.09.19

Anne-Kristin Løes

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1 Introduction

Over the last years, European governments as well as the European Union (EU) have encouraged the expansion of organic farming systems. However, the current regulations on the use of phosphorus (P) inputs in organic farming may effectively prevent a further expansion. P is an essential macronutrient for crop plants. The total quantity of P naturally present in most soils is low, with most of what is present in a form inaccessible by crop plants. The maintenance of soil P levels at a point which is not limiting for crop growth is challenging in organic farming due to the restrictions on the use of permitted P inputs in EU regulations for organic production. These regulations exclude conventional mineral P fertilisers. The principal authorised P sources are rock phosphate, some P-containing recycled organic materials such as compost from source-separated household waste and/or green waste from recreational areas, and animal manures with some restrictions (Regulation EU 2018/848 art. 1.9.5). These P sources are often inadequate to replace P exported in crops and losses, and organic farmers often encounter soil P deficits (Cooper et al. 2018; Løes and Ebbesvik 2017). A possible alternative for organic farmers might be the use of phosphate salts precipitated from certain wastewaters, such as struvite ($MgNH_4PO_4$) recovered from municipal sewage. Recovered struvite has been shown to be an effective P fertilizer in both conventional and organic agricultural systems (for example, Improve P project - https://improve-p.uni-hohenheim.de/en - and over 50 studies summarised in SCOPE Newsletter n°s 43, 121 and 122 -www.phosphorusplatform.eu). Recovered struvites are authorised, either case-by-case or in general, as a fertiliser in several EU countries (Belgium, Denmark, Germany, The Netherlands) and in Canada, Japan, Switzerland, the UK and 42 US States (see summary in SCOPE Newsletter n°124). The EU's "Expert Group for Technical Advice on Organic Production" (EGTOP), Report of 2/2/2016 states "the use of Struvite as a fertilizer should be considered to be in line with the objectives, criteria and principles of organic farming, … if Struvite were authorized under Reg (EC) 2003/2003, the Group recommends that it should be included in Annex I provided that the method of production ensures hygienic and pollutant safety". It is now expected that recovered struvite will be authorised under the new EU Fertilising Products Regulation (FPR) EU 2019/1009 (via the "STRUBIAS" process, https://www.phosphorusplatform.eu/images/download/STRUBIAS-Seville-conclusions-27-9-18.pdf) and the FPR and STRUBIAS specify hygiene and pollutant safety criteria, so opening potential authorisation for use in organic farming.

Struvite is not water soluble like many conventional mineral P fertilisers but is soluble in Neutral Ammonium Citrate. Its effectiveness on crops is may depend on crop and environmental conditions. Here, we assessed during 2018 the use of struvite as a supplementary P source to manure application in a perennial ley, where different amounts of slurry from organic dairy cows had been applied in a field trial since 2011.

1.1 Objective

To test the effect of struvite as a P supplementary source to manure application in an organic dairy farming system.

2 Materials and Methods

2.1 Struvite production at Hias IKS

In 1974, a municipal consortium around Hamar, SW Norway initiated an inter-municipal waste-treatment corporation called "Hamarregionens Interkommunale Avløps Samband" (Hias IKS). Hias IKS was established by the municipalities Ringsaker, Hamar, Vang (later merged with Hamar), Stange and Løten as a response to a serious eutrophication problem occurring in the Mjøsa, Norway's largest lake. The eutrophication was caused by a constant input of P, an essential nutrient for algae growth, from the poorly treated wastewater produced in these municipalities. Up to now, Hias IKS has been investing in research and development to improve P removal methods, ensuring water quality in the Mjøsa.

Phosphorus can be removed from wastewater in different ways. Today, full-scale treatment consists of primary treatment followed by sedimentation, then activated sludge followed by sedimentation and at last chemical treatment with aluminium precipitation followed by sedimentation. The solids concentrated by sedimentation go into the anaerobic digestion. The result is a stabilised sludge, a valuable material for soil amendment which contains approximately 95 % of the P coming into the wastewater treatment plant. Until 2016, aluminium chloride was applied at Hias IKS. On the one hand, aluminium chloride increases P precipitation, on the other hand it significantly reduces plant available P in the sludge. Thus since 2012, Hias IKS has been looking for a biological alternative to chemical precipitation of P. Since May 2016, all P removal has been done biologically without chemical precipitation in a 10.000 PE (personal equivalents) prototype (Hias process) by P-accumulating organisms (PAO). PAOs are located on plastic carriers (Figure 1) that are transported between aerobic and anaerobic zones, following the waste water in a continuous process. Beside the high accumulation of phosphate, PAOs promote both the degradation of organic material (volatile fatty acids) and the reduction of ammonium to N_2 via nitrification and denitrification (Saltnes, Sørensen, and Eikås 2017). The bioP-sludge, with highly available P, is separated in a disc filter and phosphate is released in an anaerobic stripper. The phosphate in the reject water derived from stripping of bioP-sludge and the subsequent anaerobic digestion of all the sludge, is precipitated by addition of magnesium. The magnesium—phosphate precipitate is called struvite (Figure 2). In 2017, Hias-staff produced a test batch of struvite and they aim for upscaling the whole plant to produce struvite within few years (Eikås et al. 2018). Table 1 shows the chemical characteristics of the struvite used in our field experiment.

Table 1 *Chemical characteristics of the struvite used in the field experiment (n=1)*

NH_4	N	P	K	Ca	Mg	Mn
---g/kg dry matter---						
54	54	116	0.3	1.2	92	0.2

Figure 1. *Plastic carriers for location of bacteria to accumulate P from waste water, placed on top of crystals of struvite (magnesium-ammonium phosphate) precipitated from waste water at the Hias IKS waste-water treatment plant, Hedmark, Norway. Photo: VA-Nytt (forskning.no)*

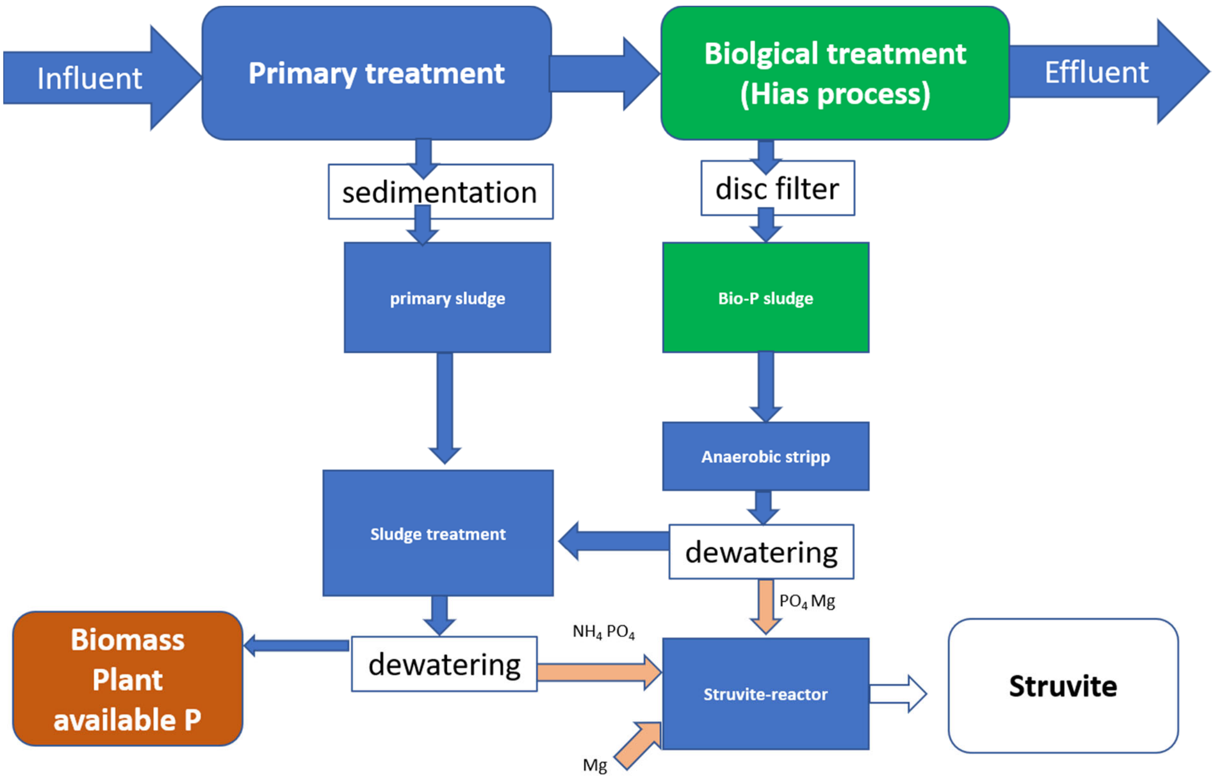

Figure 2. *An overview of the steps for future waste water treatment in Hias IKS. Source: Hias IKS*

2.2 Study site and experimental design

The experiment described herein is a continuation of a long-term study established in 2011 at Tingvoll farm, NW Norway. This area has a temperate, humid climate, with annual mean temperature of 5.6°C (1972-1990; Aune 1993) and a mean precipitation of 1160 mm (1972-1990; Førland 1993). For the growing season of 2018, from April 1 to September 30 (Figure 3), mean soil temperature 0-20 cm (recorded in 10 and 20 cm depth) and total precipitation were, 12°C and 595 mm.

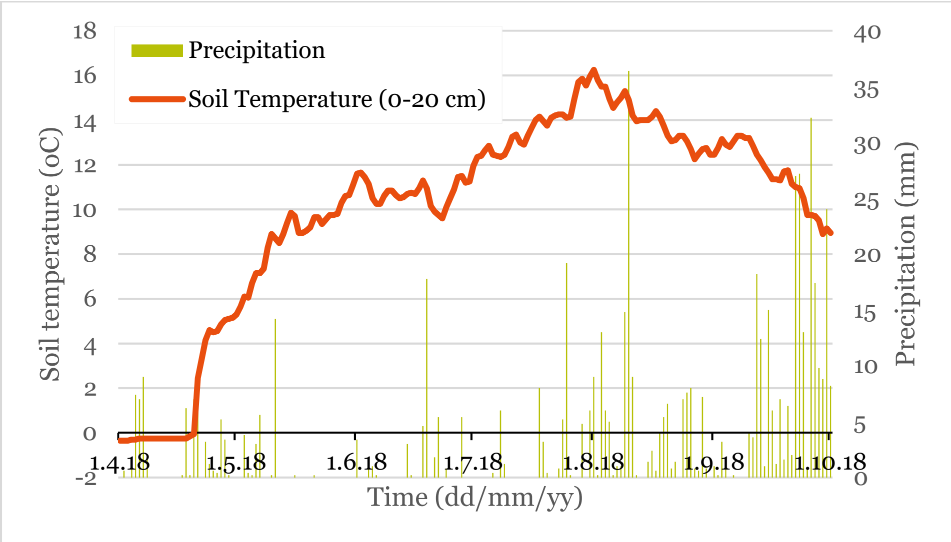

Figure 3. *Rainfall and soil temperature in the period from 1/4/2018 to 1/10/2018 at Tingvoll.*

The soil texture of the experimental soil consists of loamy sand, with about 11% of soil organic matter (SOM) and a medium to low P concentration, average level of P-AL (ammonium-acetate lactate soluble P) being 28,7 mg/kg in the topsoil (0-20 cm) (Løes et al. 2013). In 2011, the experiment, called SoilEffects, was established to test the application of different rates (0, 110 and 220 kg N ha^{-1}) of anaerobically digested and non-digested slurry (also called manure in this report) from organic dairy cows on arable and grass-clover ley systems, each one with four replicate plots (plot size = 3 m × 8 m). In 2014, the arable system was converted to grass-clover ley, giving 8 replicates of each treatment on perennial ley since that season, re-established with barley or oats as a cover crop each 5-6 year (2014, 2019). In 2018, when the crop was a 4th year ley, half of the plots received 828 g per plot of struvite (96 g P per plot). This amount comprises 4 g P per m^2, or 40 kg P per ha.

The struvite was applied on April 19 (Figure 4), followed by manure application on April 24 and 25. Struvite was applied once in early spring, whereas the manure was split in application, giving 2/3 in April and 1/3 after the 1st cut of the ley. Struvite was obtained from Hias IKS, Hedmark, Norway (for more details see section 2.1) in size comparable to sand. The treatments of the three factors experiment consisted of: two organic fertilizer types (digested (D) and undigested manure (U)), three organic fertilizer application rates (0, 110 (low) and 220 (high) kg N ha^{-1}), and application or not of struvite (without (S-) and with (S+)).

Figure 4. *Application of struvite in the field, on April 19, 2018. Photo: Anne de Boer, NIBIO.*

2.2 Soil sampling and analyses

Samples of topsoil (0-20 cm) from each plot and composite samples from a deeper soil layer (20-40 cm) from each treatment were collected on April 17 and September 19, 2018. Each sample was a composite sample of 6 soil cores, taken at fixed points at all soil sampling occasions. Soil chemical analyses (AL-extractable P, K, Mg, Ca, Na; Olsen-P, loss on ignition (L.I.) and pH (H_2O)) were performed by Eurofins (Norway). Measurement of soil P sorption capacity was carried out according to Sims (2000). P extractions were performed at the laboratory of Hias IKS, and P concentrations were analysed by SYNLAB Analytics & Services Norway AS (Hamar, Norway). Phosphorus Sorption Index (PSI) per kg of air-dry soil (Sims 2000) was calculated as:

$$PSI\ (L\ kg^{-1}) = \frac{X}{\log C}$$

Where:

$$X = P\ sorbed\ \left(mg\,\frac{P}{kg}\right) = \frac{75\ mg\,\frac{P}{L}\,x\ 0.020\ L}{0.001\ kg\ soil}$$

$$C = P\ concentration\ at\ equilibrium\ \ after\ 11\ days\ (mg\ L^{-1})$$

The principle in the Sims method is to mix soil samples with a solution of KH_2PO_4 with known concentration; and then measure P concentration in the solution after centrifugation and after the solution achieves an equilibrium, approximately after 18 hours. The PSI is then calculated by dividing P sorbed by log of P concentration at the equilibrium (C). It is recommended to measure the P concentration (mg/L) twice, after centrifugation and after 18 hours when a final state of equilibrium is achieved. In our study, P concentration was only measured once, after 11 days. Hence, in the formula above, the "X" is a constant, and "C" varies according to the measured P values.

A high value of PSI indicates that the soil has a high capacity to adsorb phosphate ions. Reductions in PSI could be expected by addition of phosphate to the soil.

2.3 Plant sampling and nutrient composition analyses

Ley plants were manually harvested from each plot on June 5 (early summer) and 28 August (autumn) 2018, dried and weighted. Total yield of dry matter (kg/m^2) was calculated for each plot. The harvest plot size was 7 m x 1.2 m. Plant samples from each plot and harvest (n= 80) were shipped to Actlabs for the determination of nutrient concentrations (P, S, K, Mg, Ca, Na, Fe, B, Cu, Mn, Zn, Al).

2.4 Data analyses

Statistical analyses were performed using Jasp 0.9.2. The data were checked for normality and homogeneity of variances to meet the assumptions of ANOVA. Factorial ANOVA and Repeated Measures ANOVA (RMANOVA) were performed to test effects of manure type, manure rate, struvite application and their interaction on soil chemical properties in autumn and total ley yield, and total ley nutrient concentration. Nutrient concentrations were measured at each cut (see chapter 7), but significant differences between treatments were only obtained for the combined canopy and hence only total nutrient concentrations (in 1^{st} + 2^{nd} cut) are presented here. Statistical tests were considered significant when p-value was less than or equal to 0.05. Partial eta-squared (*partial* η^2) was measured for significant statistical results to express the proportion of variance that a variable explains which is not explained by other variables. Partial η^2 varies from 0 to 1, where 0.2 is considered a 'small' effect size, 0.5 represents a 'medium' effect size and 0.8 a 'large' effect size.

Soil P-AL content (kg ha^{-1}) was calculated multiplying P concentration (P-AL) to the topsoil (0-20 cm soil depth) dry weight, 2060 ton ha^{-1}. Correlation between P concentration (P-AL and P-Olsen) and PSI for the top soil layer (0-20 cm) were calculated for both P-AL and P-Olsen. Soil P change represents the difference between spring and autumn values for P-AL and P-Olsen, and PSI is the difference (PSId) between PSI in autumn (PSIa) minus PSIs in spring (PSIs) values. Changes in topsoil P contents (kg/ha) and P budget (kg/ha) from previous years since 2011 were calculated based on the published (Løes and Ebbesvik 2017) and unpublished results from the SoilEffects field experiment (see section 2.2). P budget was calculated as the total P applied (manure or manure plus struvite) minus P removed in yields. Our results are presented in kg/ha and it corresponds to kg/m^2= ton/ha/10; 1 daa = 1 ha/10.

3 Results

3.1 Soil characteristics before application of struvite, and changes during the growing season without struvite

Since 2011, the experimental field has been receiving manure application, therefore differences in soil chemical characteristics were expected before the start of the struvite experiment. The values of all soil characteristics which were measured are shown in Chapter 7 (Attachments). The amount of manure had a significant effect on all soil characteristics except L.I. and Na-AL (Table 2), whereas the type of manure and its combined effect with application rate had a significant effect only on K-AL. For all evaluated soil characteristics, the treatment with the highest rate of undigested manure application had significantly the highest values. Except for L.I., control without manure application showed significantly the lowest values for the soil properties assessed. By April 2018, soil chemical characteristics varied between treatments as follows: pH from 5.7 to 6.2; P-AL from 2.3 to 3.5 mg/100g dry soil; P-Olsen from 0.5 to 0.9 mg/100g dry soil; K-AL from 4.5 to 10.5 mg/100g dry soil; Mg-AL from 4.5 to 9.4 mg/100g dry soil; Ca-AL from 82 to 135.3 mg/100g dry soil; Na-AL from 5.3 to 4.9 mg/100g dry soil; L.I. from 7.9 (lowest rate undigested manure) to 8.7 % (highest rate undigested manure).

Even if a long-term increase with manure application was found for both P-Olsen and P-AL (Table 2, Figure 7 a, c), an (insignificant) increase was found for P-AL from spring to autumn only in the treatment receiving high amount of undigested manure (Attachment). For P-Olsen, slight increases were found in all treatments except the control (Attachment). For PSI, we could expect that the levels in spring 2018 would be somewhat lower in treatments receiving high amounts of manure almost each year since 2011, but that was not the case (Attachment). On average for the 8 replicate plots in each treatment, PSI values varied between 906 with low and 922 with high level of digested manure, with 915 for the Control. Hence, the manure application in 2018 would likely not affect PSI, and any change in PSI would most likely be due to application of struvite.

Table 2. *Partial effect size values (partial η^2) of significant factorial ANOVA results illustrating the effect of manure type and manure application on soil characteristics*

Source	pH	P-AL	P-Olsen	K-AL	Mg-AL	Ca-AL	Na-AL	L.I.
Manure type (M)	ns	ns	ns	**0.11***	ns	ns	ns	ns
Manure application rate (MR)	**0.68****	**0.50****	**0.47****	**0.62***	**0.56****	**0.50****	ns	ns
M × MR	ns	ns	ns	**0.19***	ns	ns	ns	ns

Asterisks represent significant differences (**$p < .001$; * $p \leq 0.05$) between treatments (ANOVA, *n=8*); ns=not-significant; L.I. = loss on ignition.

3.2 Effect of struvite application on soil characteristics

Application of struvite had little or no effect on characteristics of the deeper soil (20-40 cm) (Chapter 8, Attachments). Results presented here are from the topsoil (0-20 cm).

Soil pH was significantly affected by the interaction of manure type, application rate and struvite (Figure 5 and Table 3). Increasing rate of manure increased soil pH, but in the presence of struvite soil pH was reduced. The magnitude of the pH reduction in soil was higher with the undigested than digested manure type. When comparing autumn to spring soil pH, treatments with struvite had small changes while treatments without struvite increased soil pH (Figure 5). Overall, manure and struvite applications significantly improved soil chemical characteristics during the experiment (Tables 3 and 4, Figures 5-8). Manure type and its interactions had no significant effect on soil properties except for soil pH (Table 3). The increase of manure application rate increased the concentrations of extractable P, K, Mg and Na in soil, while application of struvite increased soil P and Mg concentrations (Table 3).

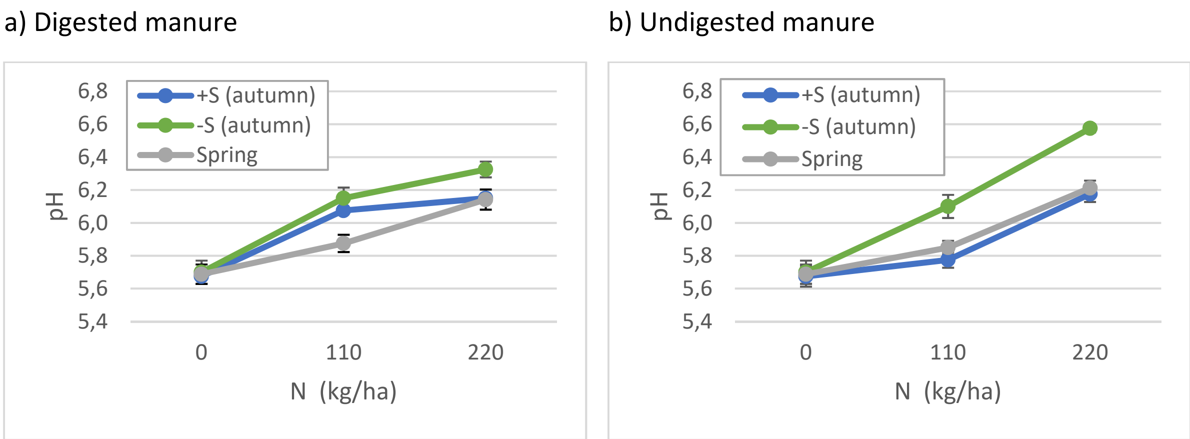

Figure 5. *Soil pH in spring (17/4/18) before application of struvite, and in autumn (19/9/18), 5 months after application of struvite, in treatments with two levels of manure application (110 and 220 kg N ha^{-1}) for two types of manure. Error bars indicate standard error (n=4).*

There was no significant difference between the average soil Mg-AL and P-AL concentrations for the anaerobically digested and non-digested manure in autumn. Hence, results of these treatments were combined according to the manure application rate in high (220 kg N/ha) and low (110 kg N/ha).

Soil Mg-AL concentration (Figure 6) at autumn ranged from 4.1 for the control (without manure and struvite application) to 13.4 mg /100 g air-dry soil for the treatment with the highest rate of manure plus struvite. Treatments with struvite had between 19 and 33% more soil Mg-AL than treatments without struvite application.

***Table 3**. Partial effect size values (partial η^2) of significant factorial ANOVA results illustrating the effect of three factors (manure type, manure rate, and struvite application) on soil characteristics*

Source	**pH**	**P-AL**	**P-Olsen**	**K-AL**	**Mg-AL**	**Ca-AL**	**Na-AL**
Manure type (M)	ns	ns	ns	ns	Ns	ns	ns
Manure application rate (MR)	0.84**	0.49**	0.51**	0.69**	0.61**	0.49**	0.43**
Struvite (S)	0.38**	**0.32****	**0.19***	ns	**0.26***	ns	ns
M × MR	0.25*	ns	ns	ns	Ns	ns	ns
M × S	**0.11***	ns	ns	ns	Ns	ns	ns
MR × S	**0.20***	ns	ns	ns	Ns	ns	ns
M × MR x S	ns	Ns	ns	ns	Ns	ns	ns

Asterisk represent significant differences (**p < .001; * $p < 0.05$) between treatments (ANOVA, $n=4$); ns=not-significant.

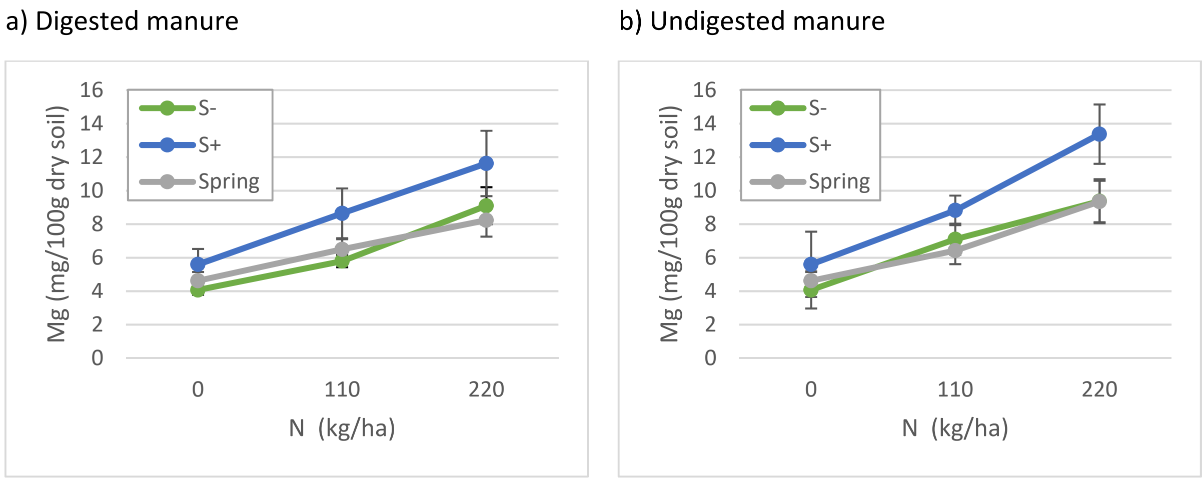

***Figure 6** Soil Mg-AL in spring (17/4/18) before application of struvite, and in autumn (19/9/18), 5 months after application of struvite, in treatments with two levels of manure application (110 and 220 kg N ha^{-1}) for two types of manure. Error bars indicate standard error (n=4).*

Struvite is not readily water soluble (Rech et al. 2019), nevertheless our results show that at least part of the struvite was solubilised and entered the soil-plant continuum. In spite of removing two harvests of ley plants, soil extractable P (P-AL and P-Olsen) concentrations in mid-September were significantly higher in the treatments with high rates of manure application and struvite (Figure 7). When compared with the treatments without struvite, struvite application increased soil P-AL concentrations between 26% and 47%. For the PSI, the effects were less clear. For one treatment, with digested manure at low application rate, PSI was lower after application of struvite. However, this treatment also had initially the lowest value (spring value 902). For other treatments, PSI seemed to increase, but only very slightly (about 1.4%), and effects were not statistically significant (Table 4).

Table 4. *Phosphorus Sorption Index (PSI) in autumn, numbers inside blankets are the standard deviation of the mean (n=4)*

Manure	Application rate (kg N/ha)	Without struvite	With struvite
No manure	0	911 (±26)	923 (±36)
Digested	110	915 (±17)	908 (±32)
	220	909 (±37)	923 (±42)
Undigested	110	904 (±19)	905 (±31)
	220	910 (±32)	914 (±49)

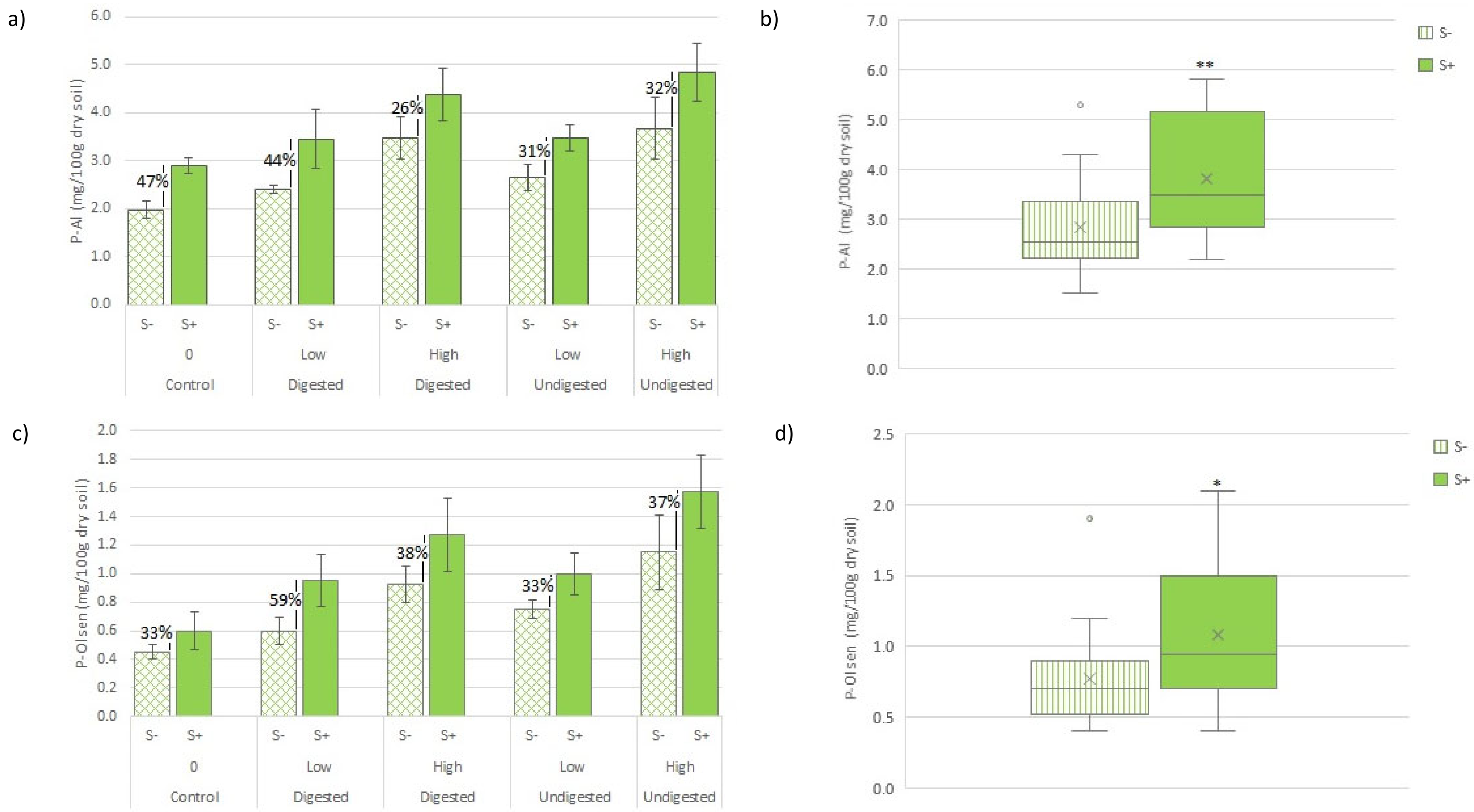

Figure 7. *Soil P-AL (a) and P-Olsen (c) concentrations on September 19 (2018), 5 months after spring application of struvite, in treatments with two levels of manure application (110 and 220 kg N ha^{-1}). Percentages indicate the P concentration difference between treatments with and without struvite. Error bars indicate standard error (*n = 4*). Struvite effect on soil P concentrations (b,d). Asterisk represent significant differences (***$p < 0.001$; * $p <= 0.05$*) between treatments with and without struvite (ANOVA,* n=20*).*

P applied to the soil by manure and struvite, which is not taken up by plants during the growing season, could be expected to decrease PSI values. Since the variation in PSI levels between treatments in spring was larger than the changes in PSI from spring to autumn, we here present the changes in PSI (PSId) to study how they correspond to the changes in soil P concentrations (**Figure 8).** Differences in P-Olsen and P-AL concentrations (Pc) are shown as spring minus autumn values, so that a decrease will be a positive number. These characteristics are supposed to decrease with plant growth, unless high applications of P are given. A positive number indicates a consumption of soil P. Potential increases will be shown as negative numbers. Negative values of Pc may reduce PSI, or to increase it to a smaller extent. Hence, the differences in PSI (PSId) are shown as autumn minus spring values, so that an increased binding capacity will be a positive number.

As shown in Figure 8, we did find a positive correlation between Pc and PSId for the top soil layer (0-20 cm). Soil P-AL concentrations increased only with application of struvite, and the five blue points to the left in Figure 8 all represent treatments with struvite applied; from left the treatments with high level of manure, then low manure applications and then the control with struvite. For P-Olsen, a negative difference (increase from spring to autumn) was found in all treatments except in the control, but the increases were higher with struvite. The order of orange points in Figure 8 (P-Olsen) is not exactly the same as for P-AL, which shows that both struvite and high manure application can increase soil concentrations of P-Olsen and cause a smaller increase in PSI. As expected, a significant relationship was found between Pc for P-Olsen and P-AL ($R^2 = 0.78$). The relationship between PISd and Pc was stronger for P-Olsen than for P-AL; $R^2 = 0.67$ as compared with 0.49.

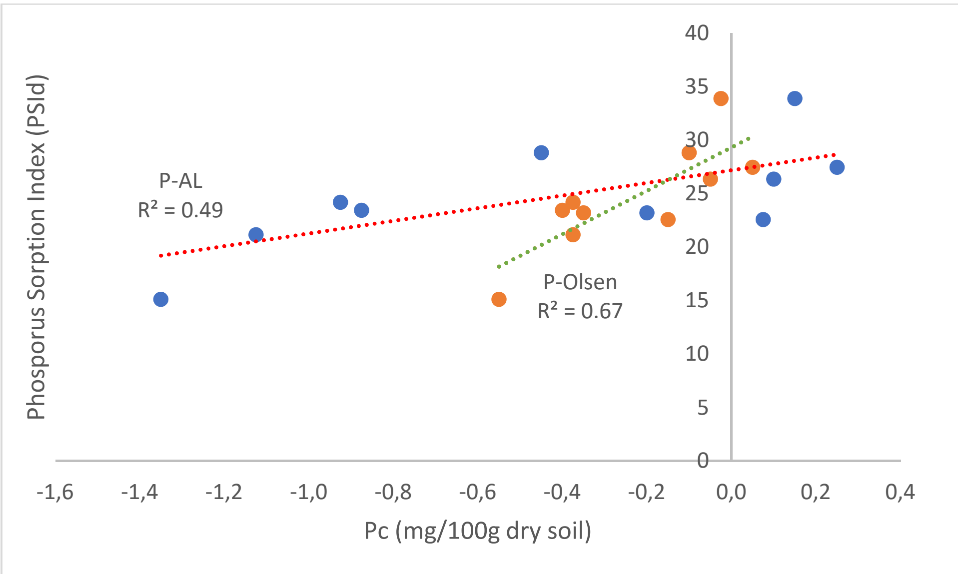

Figure 8 *Correlation between the differences in soil Pc concentrations (P-AL, P-Olsen) and P sorption index, PSI (autumn minus spring values) for the top soil layer (0-20 cm). Soil P concentration represents the difference between spring and autumn values, and PSI is the difference between autumn and spring values.*

3.3 Ley yield

In June 2018, experimental plots which had received struvite had a more vigorous growth (Figure 9). The summer of 2018 was exceptionally dry (Figure 3), and the cuts of the first harvest were low (Table 5) as compared with average values of former seasons (Løes and Ebbesvik 2017).

Figure 9. *The growth of perennial ley varied significantly between the plots. Photo from June 5, 2018 by Anne de Boer, NIBIO.*

Table 5. *Dry matter production in 4th year ley; first cut, second cut and total yields, with and without application of struvite during 2018. Error bars indicate standard error (n = 4).*

Manure type	Manure Rate (kg N /m2)	Struvite	Cut	Mean (±SE) (kg DM/daa)	Total (±SE) (kg DM/daa)
No manure	0	-S	1	60 (±20)	240 (±70)
			2	180 (±50)	
		+S	1	110 (±10)	410 (±30)
			2	300 (±30)	
Digested	110	-S	1	140 (±10)	460 (±40)
			2	320 (±50)	
		+S	1	150 (±10)	590 (±80)
			2	440 (±70)	
	220	-S	1	180 (±10)	680 (±90)
			2	500 (±80)	
		+S	1	170 (±00)	650 (±80)
			2	480 (±80)	
Undigested	110	-S	1	150 (±20)	540 (±60)
			2	400 (±40)	
		+S	1	160 (±10)	600 (±40)
			2	430 (±70)	
	220	-S	1	140 (±10)	590 (±70)
			2	450 (±60)	
		+S	1	160 (±20)	590 (±40)
			2	430 (±30)	

Organic fertilizer addition rates and struvite application significantly affected total ley yield, $p<.001$; *partial* $\eta^2= 0.582$ and $p= 0.026$; *partial* $\eta^2= 0.131$ (Figure 10). Whereas there was a significant increase in yield levels for the control and the low manure application level with application of struvite, the difference between yields with and without struvite was not significant with the high level of manure application. High rate of digested manure without struvite treatment had the highest total ley yield production (0.678 kg m^{-2}) and control without manure and struvite had the lowest (0.240 kg m^{-2}).

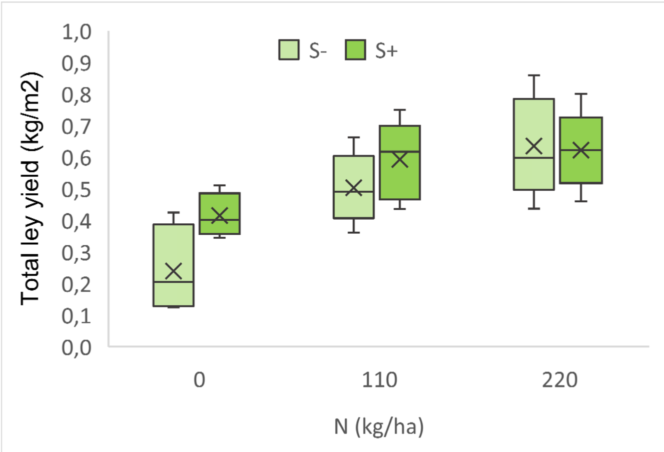

***Figure 10**. Dry matter production in 4th year ley; total yields, with and without application of struvite during 2018. Error bars indicate standard error (n = 4).*

3.4 Plant nutrient concentrations

Overall, manure addition rate significantly affected the concentrations of N, P, S, K, Mg, Ca, Cu, Mn and Zn in the aboveground plant tissue (Chapter 8, Attachments), while manure addition rate and struvite interaction affected N, P, Mg and Ca concentrations (Figure 11 and Table 5). The increase of manure addition rate reduced N, Mg and Ca concentrations in the ley canopy, and the magnitude of this reduction was influenced by the presence of struvite. Control (without manure and with struvite) showed the highest plant nutrient concentrations of N (5% of DM), Mg (0.7%) and Ca (1.4%), but in the presence of manure, struvite treatments had lower N and Ca concentrations than treatments without struvite. Mg concentrations were very similar in treatments with and without struvite at the same manure application rate. Plant P concentration was significantly higher in the treatments with struvite and higher manure application than in treatments without struvite and lower manure application. The ranked order from the highest to the lowest P plant concentration were: DH+S> Control+S> UH+S> UL+S> DH+S> DH-S> UH-S> UL-S> DL-S> Control-S. Treatments with struvite exported with the crops a higher amount of P than treatments without struvite (Figure 12). Total P content exported with the crop ranged from 7 (no manure; no struvite) to 29 kg P /ha (high rate of manure plus struvite).

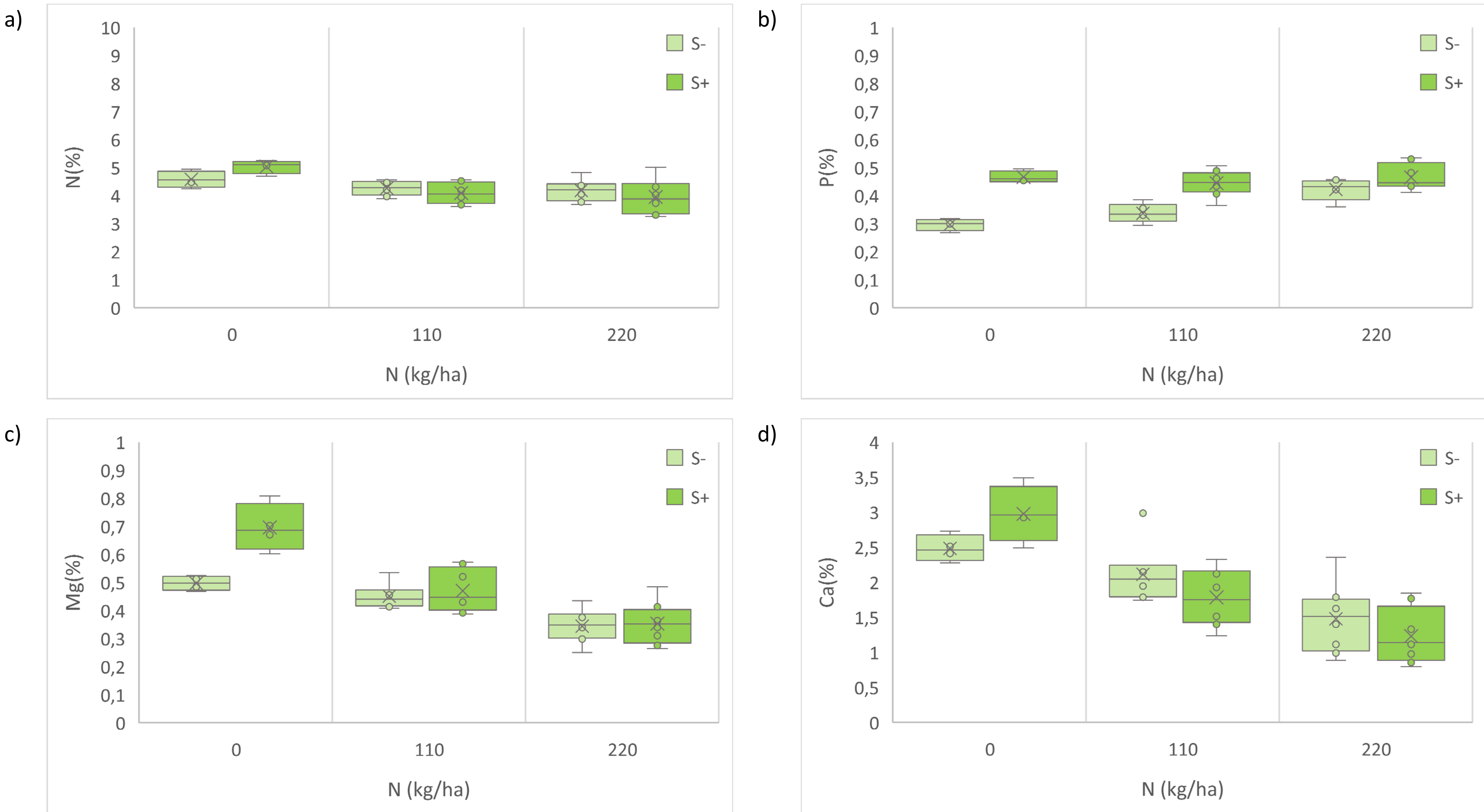

Figure 11 *Total N (a), P (b), Mg(c) and Ca (d) concentrations in ley dry matter five months after the application of different rates (0, 110 and 220 g N ha^{-1}) of digested or undigested manure and struvite.*

Table 6 *Partial effect size values (partial η^2) of significant factorial ANOVA results illustrating the effect of tree factors (manure type, manure rate, and struvite application) on cumulative nutrient concentrations in ley canopy in 2018*

Source	**N**	**P**	**S**	**K**	**Mg**	**Ca**	**Fe**	**B**	**Cu**	**Mn**	**Zn**	**Al**
Manure (M)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Manure application rate (MR)	0.50**	0.43**	0.32*	0.82**	0.76**	0.72**	ns	0.30*	0.78**	0.59**	0.26**	ns
Struvite (S)	ns	0.74**	ns	ns	0.31**	ns	ns	ns	ns	ns	ns	ns
M × MR	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
M × S	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
MR × S	**0.16***	**0.40****	ns	ns	**0.37****	**0.21***	ns	ns	ns	ns	ns	ns
M × MR x S	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Asterisk represent significant differences (**p < .001; * $p < 0.05$) between treatments (ANOVA, $n=4$); ns=not-significant.

3.5 P balance

Total P content (kg P/ha) in the harvested ley canopy plus in the top soil and sub soil of the treatments in autumn ranged from 108 kg P /ha in the control treatment (without manure and struvite applications) to 184 kg P/ha in the treatments with the highest rate of manure and struvite application (Figure 12). Total P content increased with the increase of manure application rate, and with application of struvite. The content of P removed with the canopy was also higher in the struvite treatments than in the treatments without struvite. However, even after harvesting, the P content in the top soil of the struvite treatments were about 29-47% higher than in the treatments without struvite. This shows that a significant part of the struvite P was not (yet) taken up by the plants. Hence, it is a bit surprising that the struvite did not reduce the PSI, as discussed in section 3.2.

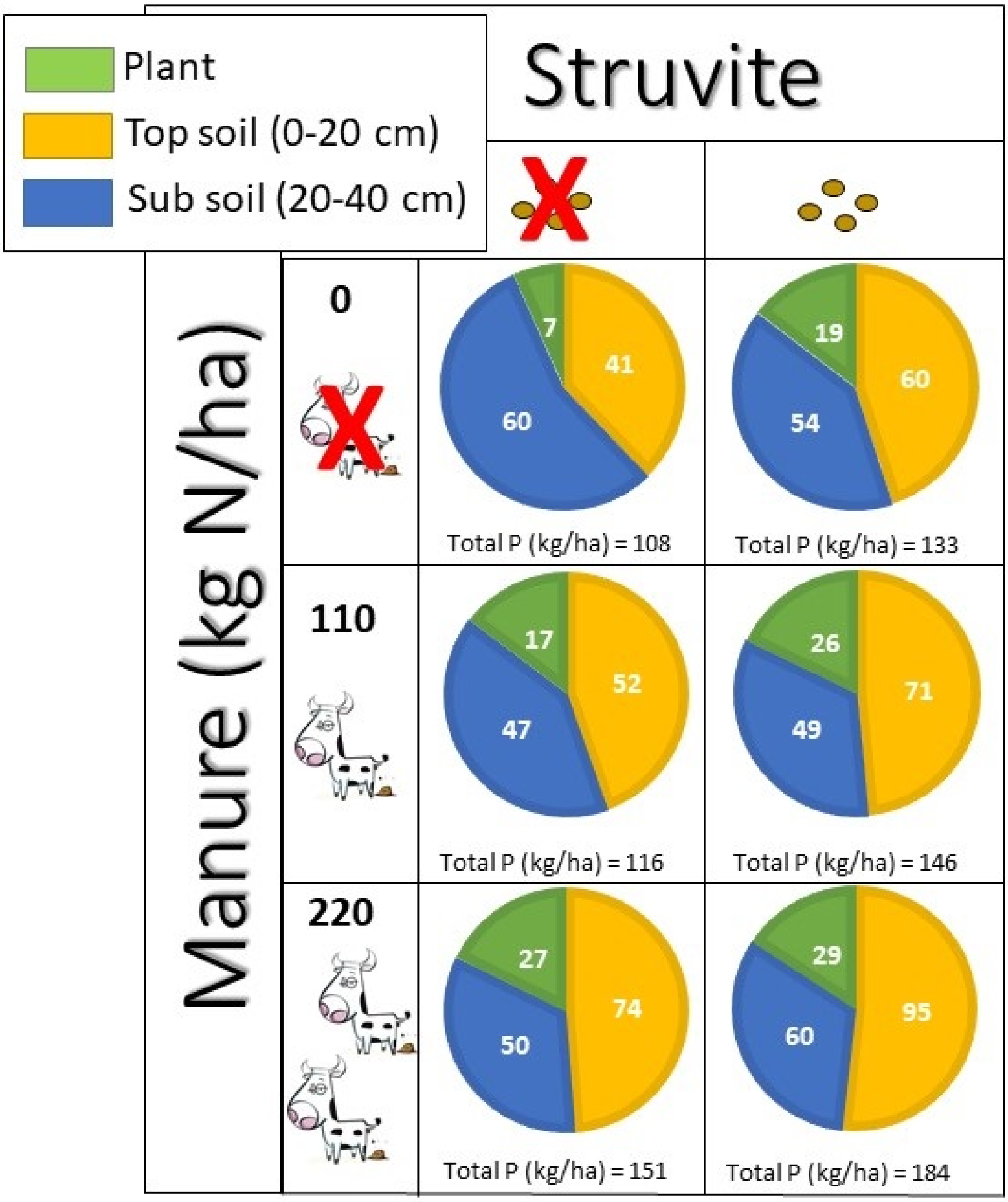

Figure 12 *Total P content (kg P / ha) in the top soil, subsoil and ley dry matter after the application of low and high rates of manure and struvite.*

Table 6 shows the changes in the topsoil P contents and the P budget from 2011 to 2018. From 2011 to 2017, treatments did not receive struvite. Only in 2018, struvite was applied in half of the experiment. Overall, topsoil P content increased in 2013 when compared to 2011 levels. The highest rates of manure application had the greatest increases of P content (2011 vs 2013), from +18 to +26.3 kg P/ha. From 2013 to 2016, topsoil P content decreased, losses ranged from -14 kg P/ha in the control (no manure) to -30 kg P/ha in the high rate of undigested manure application treatment. Overall, in 2018, treatments showed an increase in topsoil P levels, however the raise was not always big enough to overcome the soil P deficit of the previous years, showing negative values. Except for the control and low rate of undigested manure treatment, the topsoil P enhancement in the struvite treatments were higher than in the treatments without struvite.

In 2011, P budgets (applied P minus removed P) were negative only for the control (-11) and the treatment with lowest rates of undigested manure (-3). However, in the next years (2013-2016), the amount of P removed with the canopy was higher than the quantity of P added with the manure, leading to a decrease in the P budget of all treatments. In 2018, all treatments that did not receive struvite show a negative P budget (-7.9 to -2.1), while all treatments that receive struvite had a positive P budget (+21 to +35).

Table 6*. Changes in topsoil P contents from 2011 to 2013 , 2013 to 2016 and 2016 to 2018 and P budget for low (110 N ton/ha yr) and high (220 N ton/ha yr) applications of digested and undigested manure Data from the previous years on the effect of manure application on P content of the field experiment over the years 2011-2016* (Løes and Ebbesvik 2017) *and results of 2018.*

Treatment		Changes in topsoil P contents (kg/ha, 0-20cm depth)				P budget (kg/ha)				
		2011 vs 2013	2013 vs 2016	2016 vs 2018		2011	2013	2016	2018	
Manure type	Rate			-Struvite	+Struvite				-Struvite	+Struvite
No manure	0	+3.6	-13.9	+11.8	+5.7	-11	-9	-9	-7.1	+21
Digested	Low	+12.4	-24.7	-3.1	+7.2	+1	-10	-1	-3.3	+26
	High	+18.0	-22.1	-4.6	+5.7	+13	-4	+5	-6.0	+32
Undigested	Low	+17.0	-20.1	+3.6	-2.6	-3	-8	-3	-7.9	+24
	High	+26.3	-29.9	-13.9	-5.7	+15	-2	+7	-2.1	+35

4 Discussion

At spring, before the experiment started, soil pH was significantly higher in the plots with the highest rate of manure application (Table 2), ranging from 5.7 to 6.2. In autumn, the same pattern was observed regarding manure application rates, however plots which received struvite had a significantly lower soil pH than treatments without struvite, but somehow similar to soil pH at spring (Figure 5). Application of struvite seemed to acidify the soil and somehow offset the increase in pH caused by application of manure. The acidification may have been caused by the high ammonium content (5.4%) of struvite (Table 1). The content of ammonia affects its solubility in soil with various pH. Struvite has a higher solubility at acid than neutral pHs (Rech et al. 2019). Because the solubility of struvite is highly dependent on soil pH, changes in pH due to former manure application as well as the applications in 2018 may have played a significant role in our findings.

Studies have reported a high P uptake by plants in struvite-amended soil treatments under acidic or near-neutral pH conditions. In a study with six urine-derived struvites (Antonini et al. 2012), P uptake by ryegrass was similar or even higher in struvite-treated soil than in soil treated with a commercial mineral fertilizer (soil pH not informed). Bonvin et al. (2015) assessed P uptake by ryegrass from urine-derived struvite in an acidic soil (pH H_2O 5.4) and found that similar amounts of P in the plant were derived from the struvite fertilizer as from a water-soluble reference fertilizer (KH_2PO_4). In the present study, the lower soil pH in the treatments with struvite than in the treatments without struvite may have impacted struvite solubility, leading to a higher concentration of extractable P in the soil (Figure 7b and d) and in the plant (Figure 11b), and consequently affecting crop yield (Figure 10).

The interaction between struvite and manure application rate was not additive for ley yield (Figure 10), P concentrations in soil (Figure 7b and d), and plant P uptake (Figure 11b). This means that doubling the manure rate application in the treatments with struvite did not result in a corresponding increase in P content in soils and plant (Figure 12), and crop yield. The presence of struvite in the treatment without manure application (control) increased ley yield by 130%. This effect was reduced with the increasing rate of manure application. On the average, at the low and high rates, treatments with struvite produced respectively 19% and 0.4% more ley than treatments without struvite. The same pattern was observed in P content in the soil (0-20 cm) and plant. Only the content of P in the subsoil (20-40cm) increased with the raise of manure rate. The overall decrease in P contents with the increase of manure application rate may also be related with the increase in soil pH by the manure. Figure 5 shows a significant (Table 2) increase in soil pH with increase of manure application in both, treatments with and without struvite. Cattle manure amendments usually increase the soil pH (Whalen et al. 2000). Changes in the pH of soils amended with cattle manure are due to the presence of carbonates and bicarbonates, as well organic acids with carboxyl and phenolic hydroxyl groups (Whalen et al. 2000). Therefore, the high soil pH at the high manure application rate may have reduced the struvite solubility in these treatments affecting P content in the soil and plant.

When comparing the topsoil P contents data of this study with the previous years (Løes and Ebbesvik 2017) we observed a decrease in the level of P in soil for all treatments in 2016 compared to the values of 2013 (Table 6). In 2016, the P level content in the treatments with the highest rates of manure application were 22 ton/ha (digested) and 29 ton/ha (undigested) lower than the levels found in 2013. This drastic reduction in the P content can be explained by the fact that in 2014 there was no manure application, but removal of the yields and ploughing of the field (Løes and Ebbesvik 2017). In 2018, after application of manure over 4 years (2015-2018) the levels of soil P increased considerably for all treatment, and more with application of struvite. This positive budget should be seen in relation to the amount of P applied with struvite, which was 40 kg/ha. Values between 21 and 35 kg P per ha as a surplus (taken up by plants + increases in soil) correspond fairly well with the applied amount of P with struvite.

Even when applying higher amounts of manure than what may be available on many organic dairy farms (Løes and Ebbesvik 2017), it was not possible to maintain soil P concentrations over the years, or to reduce soil PSI levels. With the rather low soil P concentrations, it would have been fortunate to increase the soil P status. Except for 2011 and treatments with the highest rates of manure application in 2016, the amount of P removed by the yields was always higher than the amount of P applied with the manure (Table 6) in the year. Plants may take up the applied P and even explore more soil P with higher availability of other nutrients, such as N. In 2018, treatments without addition of struvite had a P budget of -7.9 ton/ha for the treatment with the lowest rate of undigested manure and -2.1 ton/ha for the highest rate of manure application. Only in the treatments with struvite application a positive P budget was achieved. In these treatments, P budget varied from +21 tons P/ha for the control (no manure) to +35 tons P/ha for the treatments with the highest rate of undigested manure application. These results show that even on organic dairy farms it may be required to apply P fertilizers from outside the farm to replace P removed in farm products (milk, meat). The need to overcome such P deficits in organic farms in the future, reinforces the importance of our results for organic farmers. Furthermore, it would be interesting to see in subsequent seasons, the residual effects on ley yields, and plant and soil P concentrations after the application of struvite in 2018.

5 Conclusions

In conclusion, we demonstrated, under field conditions, that struvite - a recovered wastewater precipitate - could enhance P concentration levels in soils amended with manure and thus decrease negative P budgets in organic dairy farming systems, which are found at Tingvoll farm and in the SoilEffects experiment used as a basis for the experiment discussed here. Furthermore, application of struvite raised ley yield, especially in the treatments with no or low rates of manure application. The positive effects of the struvite application on the P budget and ley yield supports that struvite should become permitted as a P input in organic farming systems, to help farmers to deal with P deficits and consequently loss of productivity over time. Increasing, or even maintaining, soil P concentrations by relatively high applications of animal manure may not be easy, since plants seem to take up the P before the soil is enriched, as shown in the present study.

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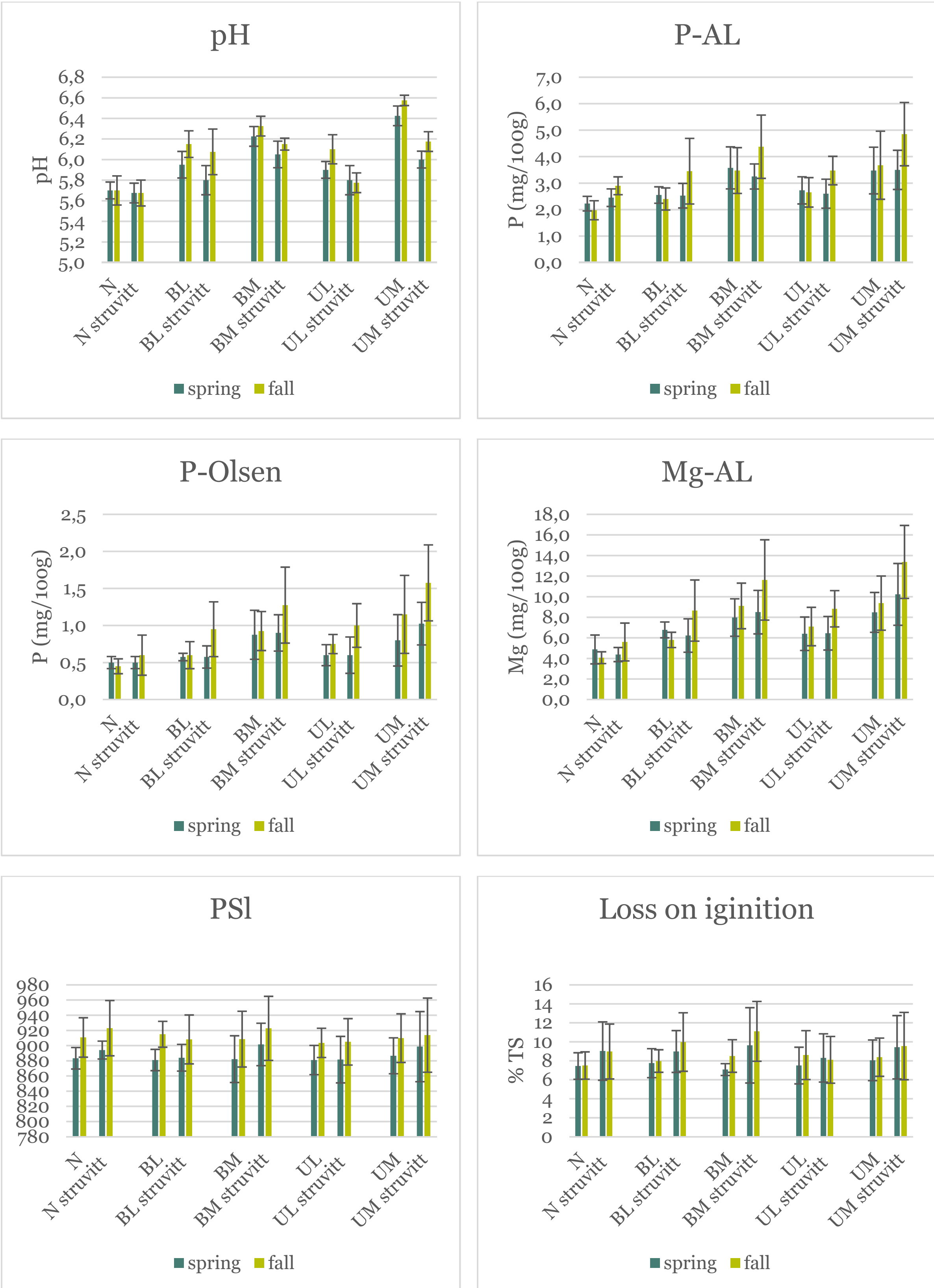
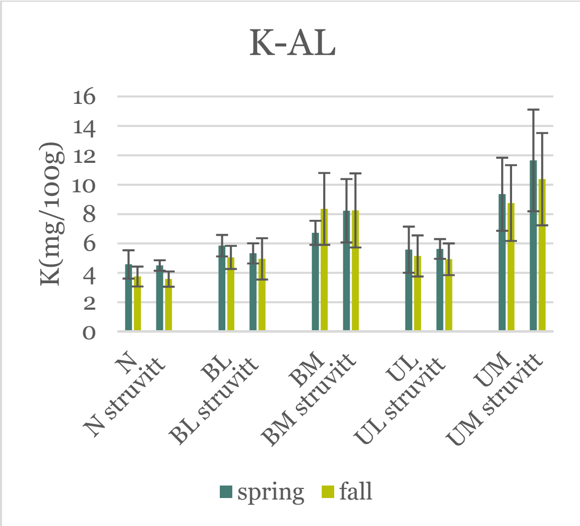
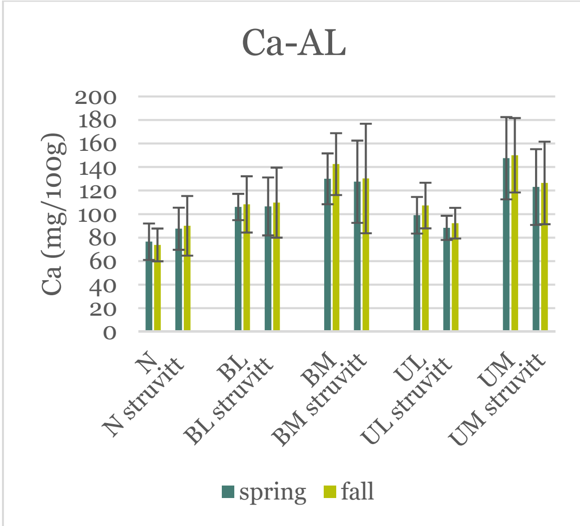
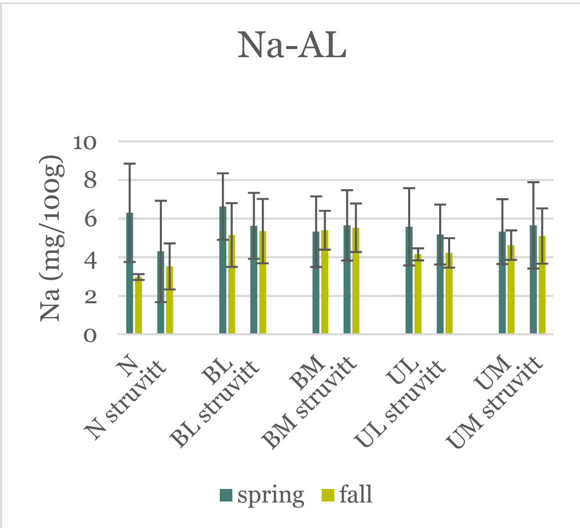
7 Attachments



Soil chemistry before (spring) and 5 months after (autumn) the application of different rates (0, 110 and 220 g N ha^{-1}) of digested and undigested manure and struvite.







Soil chemistry before (spring) and 5 months after (autumn) the application of different rates (0, 110 and 220 g N ha^{-1}) of digested and undigested manure and struvite.

Soil chemistry before (spring) and 5 months after (autumn) the application of different rates (0, 110 and 220 g N ha⁻¹) of digested and undigested manure and struvite in the 20-40 cm soil layer (n=1)

Treatments		pH				P-AL (mg/100g)				P-Olsen (mg/100g)				K (mg/100g)				Mg (mg/100g)			
		Spring		Autumn		Spring		Autumn		Spring		Autumn		Spring		Autumn		Spring		Autumn	
Manure	Rate	-S	+S	-S	+S	-S	+S	-S	+S	-S	+S	-S	+S	-S	+S	-S	+S	-S	+S	-S	+S
	0	5.7	5.8	5.9	5.9	2.3	2.2	2.9	2.6	0.4	0.4	0.4	0.4	3.3	2.6	3.2	2.6	5	3.6	3.2	2.8
Digested	110	5.7	5.8	5.8	5.9	2.1	3.3	1.9	2.4	0.4	0.4	0.4	0.4	3.4	4.2	3.3	2.6	4.1	6.2	3.4	3.4
	220	6.0	5.9	6.2	6.1	2.9	2.3	2.7	3.2	0.4	0.4	0.4	0.7	3.4	3.8	3.6	4.1	5.9	5.4	5.2	5.6
Undigested	110	5.8	5.7	5.9	5.8	3.0	2.4	2.7	2.4	0.4	0.4	0.4	0.7	4.2	3.4	3.5	3.3	8.2	4.7	5.3	4.6
	220	6.0	5.9	6.1	6.0	2.4	2.7	2.2	2.6	0.4	0.4	0.4	0.4	4.6	4.4	4.7	3.7	5.3	5.2	5.4	5.0

Treatments		Ca (mg/100g)				Na (mg/100g)				L.I. (%)				PSI			
		Spring		Autumn		Spring		Autumn		Spring		Autumn		Spring		Autumn	
Manure	Rate	-S	+S	-S	+S	-S	+S	-S	+S	-S	+S	-S	+S	-S	+S	-S	+S
	0	69	66	64	77	3.1	3.0	2.5	2.3	4.2	4.4	4.3	5.9	914	915	904	906
Digested	110	61	87	62	69	3.2	5.5	3.3	3.2	3.6	4.4	4.2	5.8	909	902	905	912
	220	82	78	83	88	3.0	3.7	3.5	4.1	5.3	4.5	5.6	5.9	931	912	888	913
Undigested	110	88	69	74	68	4.4	3.3	3.6	4.1	5.2	3.8	4.9	4.8	919	900	909	903
	220	70	76	81	73	3.1	3.6	4.0	3.3	4.4	5.0	4.8	5.7	900	928	928	947

Plant nutrient concentrations after the application of different rates (0, 110 and 220 g N ha^{-1}) of digested manure and with and without struvite application Mean (n=4), values in blankets are ± standard deviation.

Manure	Manure Rate (kg N /m2)	Struvite	Cut	N	P	S	K	Mg	Ca
				%					
No manure	0	-S	1	2.2 (0.1)	0.14 (0.01)	0.14 (0.02)	1.5 (0.3)	0.22 (0.01)	0.9 (0.1)
			2	2.4 (0.2)	0.16 (0.01)	0.17 (0.06)	1.5 (0.3)	0.28 (0.01)	1.6 (0.1)
		+S	1	2.3 (0.1)	0.24 (0.02)	0.13 (0.02)	1.3 (0.1)	0.30 (0.05)	1.1 (0.2)
			2	2.8 (0.1)	0.23 (0.02)	0.16 (0.05)	1.5 (0.1)	0.39 (0.07)	1.9 (0.4)
Digested	110	-S	1	2.2 (0.1)	0.17 (0.00)	0.10 (0.02)	2.2 (0.1)	0.20 (0.02)	0.8 (0.1)
			2	2.2 (0.2)	0.15 (0.02)	0.11 (0.01)	2.0 (0.3)	0.25 (0.03)	1.3 (0.3)
		+S	1	2.0 (0.2)	0.24 (0.03)	0.10 (0.01)	2.1 (0.2)	0.21 (0.05)	0.7 (0.3)
			2	2.0 (0.3)	0.20 (0.03)	0.11 (0.03)	1.8 (0.3)	0.27 (0.04)	1.2 (0.2)
	220	-S	1	2.2 (0.2)	0.22 (0.02)	0.12 (0.02)	3.0 (0.2)	0.17 (0.04)	0.7 (0.2)
			2	2.0 (0.4)	0.20 (0.03)	0.12 (0.01)	2.2 (0.3)	0.20 (0.03)	0.9 (0.4)
		+S	1	2.2 (0.3)	0.26 (0.01)	0.11 (0.03)	2.8 (0.2)	0.15 (0.02)	0.5 (0.1)
			2	2.2 (0.7)	0.21 (0.03)	0.12 (0.03)	2.0 (0.4)	0.20 (0.05)	0.8 (0.3)

Plant nutrient concentrations after the application of different rates (0, 110 and 220 g N ha^{-1}) of digested manure and with and without struvite application Mean (n=4), values in blankets are ± standard deviation.

Manure	Manure Rate (kg N /m2)	Struvite	Cut	Na	Fe	B	Cu	Mn	Zn	Al
				ppm						
No manure	0	-S	1	1496(1354)	68(11)	11(2)	7.7(0.5)	62(10)	25(6)	34(11)
			2	456(553)	156(73)	14(1)	11.1(0.8)	95(64)	38(12)	120(83)
		+S	1	1332(1606)	92(30)	10(2)	7.8 (1.7)	62(14)	26(5)	53(33)
			2	305(243)	193(83)	15(2)	11.2(1.9)	78(28)	41(15)	147(86)
Digested	110	-S	1	400(99)	63(12)	10(1)	6.0(0.5)	39(8)	21(4)	32(11)
			2	82(31)	140(54)	12(1)	8.0(0.7)	48(10)	31(6)	32(46)
		+S	1	304(265)	54(11)	10(3)	6.2(1.3)	37(5)	22(3)	25(3)
			2	75(18)	133(44)	12(2)	6.9(1.0)	51(11)	31(10)	25(37)
	220	-S	1	357(375)	68(20)	9(3)	5.2(1.3)	25(5)	21(2)	34(19)
			2	91(64)	127(34)	11(3)	6.2(1.4)	30(5)	27(2)	91(29)
		+S	1	167(87)	74(51)	9(2)	4.7(1.3)	29(2)	21(3)	63(91)
			2	100(51)	206(82)	10(4)	5.9(1.5)	40(11)	29(6)	171(81)

Plant nutrient concentrations after the application of different rates (0, 110 and 220 g N ha^{-1}) of undigested manure and with and without struvite application Mean (n=4), values in blankets are ± standard deviation.

Manure	Manure Rate (kg N /m2)	Struvite	Cut	N	P	S	K	Mg	Ca
				%					
No manure	0	-S	1	2.2 (0.1)	0.14 (0.01)	0.14 (0.02)	1.5 (0.3)	0.22 (0.01)	0.9 (0.1)
			2	2.4 (0.2)	0.16 (0.01)	0.17 (0.06)	1.5 (0.3)	0.28 (0.01)	1.6 (0.1)
		+S	1	2.3 (0.1)	0.24 (0.02)	0.13 (0.02)	1.3 (0.1)	0.30 (0.05)	1.1 (0.2)
			2	2.8 (0.1)	0.23 (0.02)	0.16 (0.05)	1.5 (0.1)	0.39 (0.07)	1.9 (0.4)
Undigested	110	-S	1	2.0 (0.2)	0.18 (0.01)	0.12 (0.01)	2.4 (0.4)	0.17 (0.03)	0.7 (0.2)
			2	2.3 (0.4)	0.18 (0.03)	0.14 (0.02)	2.1(0.4)	0.28 (0.05)	1.4 (0.4)
		+S	1	2.0 (0.1)	0.25 (0.03)	0.11 (0.02)	2.3 (0.3)	0.21 (0.05)	0.6 (0.2)
			2	2.1 (0.5)	0.20 (0.02)	0.11 (0.02)	1.9 (0.3)	0.25 (0.04)	1.0 (0.3)
	220	-S	1	1.9 (0.1)	0.21 (0.02)	0.12 (0.03)	2.9 (0.2)	0.13 (0.01)	0.5 (0.1)
			2	2.1 (0.4)	0.21 (0.02)	0.14 (0.02)	2.4(0.3)	0.20 (0.06)	0.9 (0.4)
		+S	1	1.9 (0.2)	0.24 (0.03)	0.11 (0.02)	2.9 (0.2)	0.15 (0.02)	0.4 (0.1)
			2	1.8 (0.4)	0.22 (0.03)	0.12 (0.03)	2.0 (0.3)	0.20 (0.08)	0.7 (0.4)

Plant nutrient concentrations after the application of different rates (0, 110 and 220 g N ha^{-1}) of undigested manure and with and without struvite application Mean (n=4), values in blankets are ± standard deviation.

Manure	Manure Rate (kg N /m2)	Struvite	Cut	Na	Fe	B	Cu	Mn	Zn	Al
				ppm						
No manure	0	-S	1	1496(1354)	68(11)	11(2)	7.7(0.5)	62(10)	25(6)	34(11)
			2	456(553)	156(73)	14(1)	11.1(0.8)	95(64)	38(12)	120(83)
		+S	1	1332(1606)	92(30)	10(2)	7.8 (1.7)	62(14)	26(5)	53(33)
			2	305(243)	193(83)	15(2)	11.2(1.9)	78(28)	41(15)	147(86)
Undigested	110	-S	1	294(415)	49(6)	10(2)	5.9(1.0)	28(4)	21(3)	17(3)
			2	177(156)	139(42)	14(2)	8.6(1.3)	49(6)	42(15)	97(35)
		+S	1	183(85)	83(53)	9 (2)	5.8(1.1)	40(7)	21(2)	73(97)
			2	109(49)	100(15)	11 (1)	7.0(1.3)	55(16)	29(5)	65(7)
	220	-S	1	107(82)	66(34)	7(1)	3.8(0.2)	22(5)	19(2)	40(46)
			2	134(154)	265(184)	10(5)	6.9(1.2)	28(8)	26(4)	215(154)
		+S	1	119(85)	51(10)	9(2)	4.3(0.2)	26(3)	19(2)	19(9)
			2	151(111)	231(165)	9(5)	5.9(2.0)	41(12)	29(14)	199(176)

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