Effects of mixed pulp mill sludges on crop yields and quality

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There is a great need for sustainable fertilisers and soil amendments, as current fertilisation practices negatively affect the environment. Pulp mill sludges (PMS) could provide a means to replace fertilisers made using non-renewable resources while adding slowly decomposing organic material to the soil and utilising nutrients from the forest industry. This study tested the effects of composted and lime-stabilised mixed PMS (CPMS and LPMS) on wheat (*Triticum aestivum*) yields and residual effect on oat (*Avena sativa*) yields in the boreal region. A two-year field experiment included two CPMS and two LPMS treatments all with additional mineral fertilisation, a mineral fertiliser treatment, and a zero-control treatment. All the fertilisers increased yields. There were no differences in crop yields between CPMS, LPMS and mineral fertiliser treatments. However, some quality characteristics and nitrogen (N) uptake were lower with all or some PMS compared with mineral fertilisation. This result suggests that part of the mineral fertilisation for cereals could be replaced by using PMS, but more information on N mineralisation from sludges is needed.

Key words: primary sludge, secondary sludge, organic fertiliser, soil amendment, recycled fertiliser, nutrient recycling

Introduction

Expansion and intensification of agriculture have caused adverse impacts on the environment (Foley et al. 2005, 2011), including increased greenhouse gas concentrations in the atmosphere (Smith et al. 2014), disturbed nitrogen (N) and phosphorus (P) cycles (Rockström et al. 2009, Steffen et al. 2015), soil degradation and biodiversity loss (Stoate et al. 2001). These problems threaten the capacity of ecosystems to produce food for the growing human population (FAO 2017).

Regarding the productivity of agricultural soils, soil organic matter is crucial. It affects the soil's chemical, biological and physical properties (Matson et al. 1997, Marinari et al. 2000, Bot and Benites 2005) and, consequently, yields (Lal 2004, Oldfield et al. 2019). A decline in soil organic carbon (C) also increases the risk of erosion (Jankauskas et al. 2007, Soinne et al. 2016) and nutrient leaching (Stoate et al. 2001). In most of Europe, soil organic C has been decreasing (Bellamy et al. 2005, Goidts and van Wesemael 2007, Capriel 2013, but see Poeplau et al. 2015). For example, in Finland, the average annual decline in mineral soils has been 0.4% or 220 kg ha^{-1} in recent decades (Heikkinen et al. 2013).

The challenges that food production faces have been proposed to be solved by agroecological, ecological or sustainable intensification, which all aim to increase production with minimised environmental impacts (Wezel et al. 2015). These strategies include increasing the use of recycled organic fertilisers in agriculture in order to restore nutrient cycles and reduce the use of fertilisers made from non-renewable resources. The recycled organic fertilisers can be either of animal or plant origin, such as meat and bone meal (Kivelä et al. 2015) or vinasse (Yang et al. 2013).

One type of recycled organic fertiliser is pulp and paper mill sludges, which are by-products from the forest industry. In Finland, the paper and pulp industry produces 578000 t of sludges yearly, which contains 230 t P and 1160 t total N, out of which 30 t is soluble N (Marttinen et al. 2017). Currently, most of the sludges are incinerated or landfilled, which is associated with adverse environmental and economic impacts (Monte et al. 2009). From the ecological sustainability point of view, the nutrients should be recycled and not discarded (Marttinen et al. 2017).

The main types of pulp and paper mill waste include primary, secondary, and deinking sludge (Monte et al. 2009). In terms of volume, wastewater treatment sludges, which are produced during the treatment of wastewater, constitute the largest residual waste stream generated by the pulp and paper industry (Monte et al. 2009). These sludges are solid wastes that come from two sources: primary sludge from the primary treatment and biological or secondary sludge from the biological treatment plants (Monte et al. 2009). The characteristics of the sludges vary depending on the production processes used in the pulp and paper making (Gendebien et al. 2001).

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Primary sludge comprises primarily wood fibres and has a high C/N ratio (Vance 2000), and it reflects the composition of wood fibre, the composition being 15–35% hemicellulose, 40–45% cellulose and 20–30% lignin (Camberato et al. 2006). Secondary sludge has higher concentrations of N and P and a lower C/N ratio (Vance 2000). These sludges are generally blended, have a polymer added and are dewatered to a 25–40% dry solid content (Monte et al. 2009). In general, the sludges are rich in organic matter and contain several plant nutrients, including N, P, potassium (K), calcium (Ca), and magnesium (Mg) (Vance 2000, Gendebien et al. 2001). In Finland, hygienisation treatment is required if a fertiliser or soil amendment contains more than 10% of biosludge, i.e. secondary sludge (the Decree of the Ministry of Agriculture and Forestry on Fertiliser Products 24/11). The sludges can be hygienised and stabilised using methods such as composting or lime stabilisation.

Using pulp and paper mill sludges as fertilisers and soil amendments have been found to have positive environmental effects. Board-mill sludge reduced P losses from conservation-tilled clay soil (Muukkonen et al. 2009). Vinten et al. (1998) reported a reduction in nitrate (NO_3) leaching after adding paper mill waste to the soil. Kirchmann and Bergström (2003) found that primary paper mill sludge reduced NO_3 leaching from agricultural soil. However, Vagstad et al. (2001) found an increase in the residual mineral N in the soil after sludge application and thus an increased risk of NO_3 leaching.

Organic fertilisers and soil amendments also have the potential to increase soil organic C (Freibauer et al. 2004, Kätterer et al. 2011) and contribute to climate change mitigation (Smith et al. 2000, Paustian et al. 2016). Several studies have found an increase in soil organic C after pulp and paper mill sludge addition (Phillips et al. 1997, Rantala et al. 1999, Zibilske et al. 2000, Foley and Cooperband 2002, Chow et al. 2003).

Pulp and paper mill sludges can also have positive effects on soil quality properties. The reported effects include an increase in enzyme activity (Gagnon et al. 2004), soil nutrient level (Sippola et al. 2003, Gagnon et al. 2004), water-holding capacity (Zibilske et al. 2000, Foley and Cooperband 2002, Chow et al. 2003), soil porosity (Phillips et al. 1997, Sippola et al. 2003) and the size of soil aggregates and aggregate stability (Zibilske et al. 2000, Chow et al. 2003, N'Dayegamiye 2006, Price and Voroney 2007), as well as a decrease in soil bulk density (Zibilske et al. 2000, Foley and Cooperband 2002, Chow et al. 2003, Sippola et al. 2003, N'Dayegamiye 2006, Price and Voroney 2007, Rato Nunes et al. 2008) and an improvement in surface water infiltration (Price and Voroney 2007).

The chemical composition of primary, secondary, mixed and deinking sludges and the amount applied varies between studies, which makes comparing different yield results challenging. It also varies between studies if the sludges are applied alone or with additional fertilisers. Some studies have found a decrease in cereal yields after sludge application (Dolar et al. 1972, Bellamy et al. 1995, Aitken et al. 1998, Simard et al. 1998), probably due to N immobilisation because of a high C/N ratio of the sludges (Bellamy et al. 1995, Mary et al. 1996). In contrast, other studies have reported yield increases (Simard 2001, Vagstad et al. 2001, N'Dayegamiye et al. 2003, Curnoe et al. 2006, N'Dayegamiye 2009, Gagnon et al. 2010, Gagnon and Ziadi 2012, Ziadi et al. 2013) or yields similar to mineral fertilisation (Rantala et al. 1999, Sippola et al. 2003, N'Dayegamiye 2006, Gagnon et al. 2010).

Studies on the effects of lime-stabilised mixed pulp mill sludges (LPMS) on crop yields are scarce, and comparisons on the yield effects of LPMS and composted mixed pulp mill sludges (CPMS) are also lacking. This study tested the effects of LPMS and CPMS on wheat (*Triticum aestivum*) yields, and the residual effect on oat (*Avena sativa*) yields, some grain quality characteristics and N uptake when mineral fertilisers were partly replaced by these types of sludges. The first hypothesis was that part of the fertilisation could be replaced by pulp mill sludges (PMS) without compromising the yield quantity or quality. The second hypothesis was that the effect on yields of CPMS and LPMS is different because of the differences in their chemical composition.

Materials and methods

Description of the mixed pulp mill sludges

The experiment included four different types of mixed PMS products (produced by Soilfood Oy, formerly Tyynelän maanparannus Oy), out of which two were CPMS, and two were LPMS. Both CPMS and LPMS came from two different mills in Finland, mill A (Stora Enso Imatra) and mill B (UPM Lappeenranta). The PMS were a mixture of primary and secondary sludge from a pulp mill's wastewater treatment, comprising approximately 70% primary sludges and 30% secondary sludges. The static pile composting period was eight weeks to reach hygiene requirements for CPMS. For LPMS, lime stabilisation was performed by mixing burned lime (CaO) and slaked lime (CaOH) constituting 5% of PMS mass to raise pH to 12 for at least two hours according to Finnish fertiliser regulation. The total C content of the sludges ranged from 30 to 37% on a dry weight basis, the C/N ratio ranged from 22 to 32, and the pH ranged from 6.3 to 8.3 (Table 1). The concentration of cadmium (Cd) in sludges from mill B exceeded the maximum permissible Cd concentration for soil amendments under Finnish legislation, which is 1.5 mg kg^{-1} DM.

Table 1. Chemical composition of pulp mill sludges and the application rates of pulp mill sludges and nutrients in them in the field experiment, on a dry weight basis

Chemical composition of pulp mill sludges				
	CPMS A	LPMS A	CPMS B	LPMS B
Dry matter (%)	48	47	41	50
pH_{H2O}	7.8	8.3	6.3	7.7
C total, %	32.9	30.4	36.6	31.2
N total, g kg^{-1}	12	9.5	13	14
N soluble, g kg^{-1}	0.69	0.63	1.60	1.10
C:N ratio	27	32	28	22
P total, mg kg^{-1}	2000	1900	1500	2900
K, mg kg^{-1}	750	700	280	370
Ca, mg kg^{-1}	45 000	74 000	35 000	95 000
Mn, mg kg^{-1}	1 600	980	1 300	1 800
Zn, mg kg^{-1}	100	84	200	230
Cu, mg kg^{-1}	25	17	15	19
Pb, mg kg^{-1}	8	8	8	8
Cd, mg kg^{-1}	0.6	0.5	2	2
Organic matter, %	74.5	68.8	83.1	71.5
Application rates of pulp mill sludges and nutrients in them (kg ha^{-1}) in the four PMS treatments of the field experiment				
	CPMS A	LPMS A	CPMS B	LPMS B
Application rate of PMS	24864	24326	17661	25324
N total	298	231	230	355
N soluble	17	15	28	28
P	50	46	27	73
K	18.6	17.0	4.9	9.4
S	164	131	136	233
B	0.5	0.3	0.2	0.4
Mn	39.8	23.8	23.0	45.6
Ca	1119	1800	618	2406
Ctot	8180	7395	6464	7901

CPMS = composted pulp mill sludge; LPMS = lime-stabilised pulp mill sludge

The total C of the PMS was determined by dry combustion using a Leco CN828 analyser (Leco Corp., St Joseph, MI, USA). Total N was determined by Kjeldahl digestion (Bremner and Mulvaney 1982) and soluble N from 1:5 water extractions according to SFS-EN 13652 (Finnish Standards Association 2002). The total P, K, Ca, manganese (Mn), zinc, copper, lead and cadmium were determined after acid digestion according to SFS-EN ISO 11885:2009 (Finnish Standards Association 2009). pH was determined according to standard SFS-EN 13037 (Finnish Standards Association 2000a), dry matter gravimetrically according to standard SFS-EN 13040 (Finnish Standards Association 2000b) and the organic matter content was determined as the loss upon ignition at 550 °C for four hours (Finnish Standards Association 2000c).

Field experiment

The field experiment was established in the research fields of the University of Helsinki, Finland, (60° 13′ 21.9″ N 25° 00′ 41.2″ E) in autumn 2015. During the two cropping seasons (May to September 2016 and 2017), total precipitation was 320.5 and 274.9 mm, respectively. Monthly mean air temperatures (°C) during the growing season in 2016 were 14.2, 15.4, 17.8, 16.2 and 13.0, and in 2017, 9.8, 13.7, 16.0, 16.2 and 11.8. The soil type was sandy clay (Aaltonen and Vuorinen 1949), with pH_{H2O} (Vuorinen and Mäkitie 1955) of 6.2, 10.8% organic matter (loss on ignition) and acid ammonium acetate extractable P 7.1 mg l^{-1} and K 265 mg l^{-1} (pH 4.65; Vuorinen and Mäkitie 1955). According to Finnish guidelines, the status of the soil tests for P and K were satisfactory, Mg poor and B tolerable.

The field experiment had a factorial design. The main plot factor was stand type with three levels (Appendix 1). The factor levels were sole spring cereal, spring cereal undersown with ryegrass (*Lolium perenne*), and spring cereal sown with catch crop ryegrass. The main plots of 15 m × 10 m were randomised in four complete blocks. Stand type, i.e. catch crops and undersown crops were part of the field experiment because their effects on nitrate leaching potential in autumn were also investigated, but these effects are not addressed in this article. Stand type had no effect on the crop yields, and thus this report focuses on the effects of fertilisation. Fertilisation was the subplot factor with six levels: two CPMS and two LPMS treatments with additional mineral fertilisation, a mineral fertiliser treatment, and a zero-control treatment without PMS or mineral fertiliser. The 3 × 6 = 18 treatments were factorial combinations of the two factors, and these were arranged by randomising each fertilisation within each main plot to subplots of 2.2 m × 10.0 m. The experiment was run over two successive growing seasons: in the first season in 2016, wheat, variety 'Anniina' (Boreal Plant Breeding Ltd, Jokioinen, Finland), was grown, and in the second season in 2017, oat, variety 'Obelix' (Saatzucht Bauer GmbH & Co. KG, Obertraubling, Germany), was grown. Oat was resown because the first sowing did not sprout evenly (Appendix 1).

The quantity of PMS applied ranged from 17.7 to 25.3 t ha^{-1} on a dry weight basis (Table 1). The application rates of PMS were based on the maximum amount of soluble N allowed to be applied in the autumn in Finland (30 kg ha^{-1} N). Soluble N applied in sludge A treatments were 15 and 17 kg ha^{-1} (LPMS and CPMS, respectively) and in sludge B treatments, around 28 kg ha^{-1} (Table 1). The lower quantity of applied soluble N than planned was because the exact nutrient content of the sludges was known only after the application of the sludges. Due to the varying total N content of the sludges, the total N applied ranged considerably (Table 1). The amount of other nutrients applied from the mixed PMS also ranged widely (Table 1). The PMS were applied only once in September 2015. They were first spread on the soil surface and then mixed into the upper 10 cm of soil with a disc cultivator. No PMS were added in 2016 or 2017. The 2017 season of oat was included for detecting possible residual yield effects of the PMS applications of autumn 2015.

All PMS treatments received 250 kg ha^{-1} additional mineral fertiliser (50 kg N ha^{-1}) in spring 2016 and 400 kg ha^{-1} in spring 2017 (80 kg N ha^{-1}). Mineral fertilisation treatment received 400 kg ha^{-1} (80 kg N ha^{-1}) in 2016 and 400 kg ha^{-1} (80 kg N ha^{-1}) in 2017. The mineral fertiliser used for all fertilisation treatments was Kevätviljan Hiven Y, N-P-K:20-3-8 (Kemira GrowHow, Helsinki, Finland). Ryegrass from undersown and catch crop plots were not harvested but ploughed to the soil. Herbicides were applied in both years according to specific crop recommendations.

The yields were harvested from a 12 m^2 area from each plot with a plot combine harvester and converted into yields per hectare at 14% moisture content. Grain quality characteristics, which were hectolitre weight, 1000-grain weight, starch, and crude protein, were analysed from 2016 wheat yields. Hectolitre weight was analysed with a Grain Analyser (DICKEY-john GAC 2000, DICKEY-john Corp., Auburn, IL, USA) and 1000-grain weight with a Seed counter (Pfeuffer Contador, Pfeuffer GmbH, Kitzingen, Germany). For starch and crude protein, replicates were pooled, and only one grain sample for each stand type fertilisation treatment combination was analysed. Starch and crude protein were determined with near-infrared spectroscopy according to standard SFS-EN ISO 12099 (Finnish Standards Association 2010). Grain N concentration for wheat was calculated from crude protein concentration (Equation 1).

Grain N concentration (%) = Crude protein (%)/a [1]

where a is a coefficient of 5.7 for wheat (Sosulski and Imafidon 1990).

N uptake was calculated as uptake in harvested grain (Equation 2).

N uptake (kg ha^{-1}) = Crude protein (%)/a × yield (kg ha^{-1}) × 0.86/100 (%) [2]

where a is a coefficient as in [1]. A coefficient of 0.86 was used to convert the grain yields from 14% moisture content to 100% dry matter content.

Statistical analyses

To analyse the effects of fertiliser treatments on yield, analysis of variance (ANOVA) was performed using the GLM Univariate procedure of SPSS statistical software version 25 (IBM, Armonk, NY, USA). For the amount of yield, hectolitre weight, and 1000-grain weight, the analysis followed a split-plot ANOVA with stand type as the main plot factor and fertilisation treatment as the subplot factor. For crude protein concentration, starch concentration and N uptake, which were based on one analysed grain sample for each stand type fertilisation treatment combination, a regular one-way ANOVA was performed to compare fertilisation treatments. Tukey's post hoc pairwise comparisons were done to compare each fertilisation treatment with one another. Treatment effects with probability values above 0.05 were considered non-significant.

Results

Wheat and oat yields

Stand type, i.e. catch crops and undersown crops (the main plot factor) had no effect on the crop yields, and thus this report focuses on the effects of fertilisation treatments (the subplot factor). Wheat yields in 2016 ranged from 2358 to 3170 kg ha^{-1} and oat yields in 2017 from 6425 to 7876 kg ha^{-1} (Fig. 1).

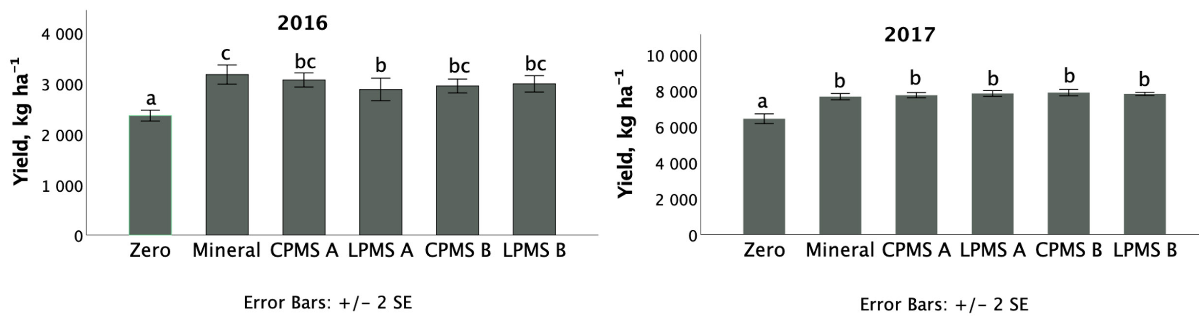

Fig. 1. Wheat yields in 2016 and oat yields in 2017 (kg ha^{-1} at 14% moisture content) in treatments fertilised by pulp mill sludges (PMS), by mineral fertilisers, or when left unfertilised. Statistically significant differences between the treatments are indicated by different letters above the bars ($p < 0.05$, Tukey's test). Error bars: ± standard error (SE). CPMS = composted pulp mill sludge, LPMS = lime-stabilised pulp mill sludge

In 2016, the first year after sludge application, all fertiliser treatments gave higher wheat yields than the zero-control treatment (Fig. 1, Appendix 2). There was no significant difference in wheat yields between the PMS treatments or between the PMS and the mineral fertiliser treatment, except for LPMS A, which produced a lower wheat yield than the mineral treatment (Fig. 1, Appendix 2).

In 2017, when all four PMS treatments and the mineral fertiliser treatment were given mineral fertilisation, there were no significant differences in oat yields between any of the fertilisation treatments (Fig. 1, Appendix 2). All fertiliser treatments gave higher oat yields than the zero-control treatment (Fig. 1, Appendix 2).

Grain quality and nitrogen uptake

There were no differences in any of the grain quality characteristics between any of the four different types of PMS (Table 2). Crude protein and N concentrations were lower with CPMS A and CPMS B sludges compared with the mineral fertilisation but did not differ from the zero-control treatment (Table 2). Crude protein and N concentrations were higher with LPMS A and LPMS B sludge compared with the zero-control treatment but did not differ from the mineral fertilisation (Table 2). N uptake was lower with both types of LPMS and CPMS B compared with the mineral fertilisation, and with the zero-control treatment compared with all other fertilisation treatments (Table 2).

Table 2. Results of grain quality characteristics and N uptake for wheat in 2016 and hectolitre weight for oat in 2017. The results are given on a dry weight basis. Letters after the values denote within-column significant differences ($p < 0.05$, Tukey's test).

Fertilisation treatment	Crude protein %	N %	Starch %	1000-grain weight g	N uptake kg ha^{-1}	Hectolitre weight kg hl^{-1}, 2016	Hectolitre weight kg hl^{-1}, 2017
Zero-control	14.2 b	2.49 b	65.8 a	26.3 b	50.3 b	80.2 b	54.5 b
Mineral	15.0 c	2.63 c	65.0 a	28.8 c	71.6 c	81.2 a	55.2 ab
CPMS A	14.5 ab	2.54 ab	65.7 a	27.9 a	66.8 ac	80.9 ab	55.4 ab
LPMS A	14.7 ac	2.57 ac	65.3 a	27.6 a	63.6 a	80.8 ab	55.7 a
CPMS B	14.4 ab	2.53 ab	65.7 a	27.9 a	64.1 a	81.2 a	55.4 ab
LPMS B	14.8 ac	2.60 ac	65.3 a	27.9 a	66.7 a	80.9 ab	55.5 ab

CPMS = composted pulp mill sludge; LPMS = lime-stabilised pulp mill sludge

The 1000-grain weight was lower with all the other fertilisation treatments compared with the mineral fertilisation, and all four types of PMS and mineral fertilisation gave higher 1000-grain yields compared with the zero-control treatment (Table 2). There were no significant differences in wheat grain starch concentration between different fertilisation treatments (Table 2).

In 2016, the hectolitre weight was higher with CPMS B and mineral fertilisation compared with zero fertilisation (Table 2). In 2017, LPMS A gave a higher hectolitre weight compared with zero fertilisation (Table 2). No other significant differences were detected in either of the years in hectolitre weights (Table 2).

Discussion

Yields

Wheat yields achieved in the field experiment with composted and lime-stabilised mixed pulp mill sludges with additional mineral fertilisation were higher than from non-fertilised plots, but in contrast to our hypothesis, showed no differences when compared with each other. Pulp mill sludges contain somewhat soluble N directly available to the plants. However, the decomposition of organic matter with a high C/N ratio may initially result in immobilisation of N (Mary et al. 1996). The yields in the field experiment were as good as the yields achieved with mineral fertilisation (same amount of soluble N), except with lime-stabilised sludge A with the highest C/N ratio of 32. Previously Vagstad et al. (2001) reported sludge types with a C/N ratio of around 30 to give mainly negative yield responses, while sludge, with a C/N ratio of 23, gave a significant yield increase in the year following sludge application. However, in our experiment, the sludge with the highest C/N ratio also received less soluble N than the other lime-stabilised pulp sludge treatment, which may also explain the lower yields.

All treatments received mineral fertilisation, but in pulp mill sludges, part of the N was assumed to originate from the soluble N pool in the sludges. In the first growing season after the autumn applications, the sludge treatments received 30 g ha^{-1} less mineral fertilisation, but three out of four of the sludges resulted in yields in 2016 similar to those achieved with mineral fertilisation only. This suggests that pulp mill sludges have the potential to be used to replace part of the mineral fertilisation. However, the small yield increase gained with 80 kg ha^{-1} N fertilisation compared with the non-fertilised control leaves room for speculation that something other than N availability restricted the yield formation. If mineral fertilisation of only 50 kg ha^{-1} could produce the yields harvested in 2016, the N in pulp mill sludges would not have contributed to yield formation, and therefore we cannot say for sure that pulp mill sludges can be used to replace part of the mineral fertilisation. In addition, it is important to note that replacing mineral N fertilisation completely with large applications of pulp mill sludges can have an adverse effect on the environment due to slow mineralisation of N, timing of which is not optimal for crop needs.The effects of sludges on yields may also originate from other than direct fertilisation effects. In Finland, mineral soils with pH generally of 5.5–6.0 benefit from liming as the optimal pH would be 6.0–6.5 (Lemola et al. 2018). The pH of lime-stabilised sludges is higher than 7, and when applied in acidic or slightly acidic soil could increase the soil pH. Furthermore, mixed pulp mill sludges contain a considerable amount of C, thereby having the potential to increase soil organic matter (Phillips et al. 1997, Rantala et al. 1999, Zibilske et al. 2000, Foley and Cooperband 2002, Chow et al. 2003), which in turn may result in improved structure or water-holding capacity in low organic matter soils and thus enhance the productivity of the soil. In fact, for an experimental field with C% as low as 1.5, Vagstad et al. (2001) detected that while similarly fertilised, both lime-stabilised and composted sludge amended plots resulted in similar or higher yields than a plot that received only mineral fertilisation. If the improved soil productivity originates from the increased organic matter it will likely last longer than just one growing season and reported results show that onetime addition of pulp mill sludges may have positive effects on yields also in the following years (residual effect) (Aitken et al. 1998, Simard 2001, N'Dayegamiye et al. 2003, N'Dayegamiye 2006). However, in the second growing season in our field experiment, oat yields from plots treated with pulp mill sludges were similar to those achieved from plots with only mineral fertilisation, which result is in accordance with Sippola et al. (2003). Our experimental field had a C% higher than 6, and therefore it was unlikely that organic amendments like pulp mill sludges would have a residual effect on soil structural properties or water retention capacity that would have impacted soil productivity.

Nitrogen uptake

N uptake was lower with one composted (CPMS B) and both types of lime-stabilised sludges when compared with mineral fertilisation, which is similar to what Sippola et al. (2003) found for some of the tested composted pulp and paper mill sludges. Lower N uptake for the pulp mill sludges suggests that although the amount of soluble N was adjusted to be close to that of the mineral fertilisation, it was not completely available for the plants, and the possible mineralisation of organic N was not optimally timed for crop needs. N'Dayegamiye (2006), in contrast, achieved as good N uptake with sludges with additional fertilisation as with only mineral fertilisation. In our experiment, only CPMS A with the second-lowest C/N ratio resulted in N uptake as high as with mineral fertilisation. Only lime-stabilised pulp mill sludge B had a lower C/N ratio and nearly the same N uptake as CPMS A, but it was found to differ statistically from the mineral fertilisation treatment. The lower C/N ratio may explain the higher N uptake compared with other pulp mill sludges, as immobilisation is more likely in organic masses with a high C/N ratio (Mary et al. 1996). Higher N uptake may also be explained by the liming effect, as liming increases the N uptake and grain N concentration (Lyngstad 1992, Soon and Arshad 2005).

Grain quality

Equally high hectolitre weights achieved with pulp mill sludges with additional mineral fertilisation and only mineral fertilisation are consistent with the findings of N'Dayegamiye (2006) but in contrast with N'Dayegamiye et al. (2003). Previous studies have reported variable effects of pulp and paper mill sludges with additional mineral fertilisation on grain N concentration compared to mineral or zero fertilisation (Simard et al. 1998, Vagstad et al. 2001, Curnoe et al. 2006, Ziadi et al. 2013), suggesting that the effects are sensitive to the chemical composition of the sludges and the amounts applied. In our experiment, lime-stabilised pulp mill sludges with additional mineral fertilisation resulted in similar crude protein and grain N concentration as mineral fertilisation. However, composted pulp mill sludges resulted in significantly lower crude protein and grain N concentrations compared with the mineral fertilisation. Grain protein concentration is affected by N availability (Peltonen and Virtanen 1994, Wooding et al. 2000, Doltra et al. 2011), which implies that in composted pulp mill sludges there might not have been enough available N for plants to use during critical stages of crop yield formation. All four types of mixed pulp mill sludges with additional mineral fertilisation resulted in lower 1000-grain weight compared with mineral fertilisation, which might be explained by inadequate nitrogen availability. However, low N rates do not seem to affect 1000-grain weight in Finnish conditions in general (Valkama et al. 2013, but see Esala and Larpes 1986).

Conclusions

Recycling nutrients from the forest industry to agriculture has the potential to reduce the use of primary fertilisers and associated adverse environmental effects. Our results suggest that part of the mineral nitrogen fertilisation for spring cereals can be replaced by using mixed pulp mill sludges applied in the previous autumn and that when applied into soil high in C, the sludges have no residual effect in the second year following the application. The use of composted pulp mill sludges resulted in lower grain N content, suggesting that the timing of N availability was not optimal. Further experiments are needed to investigate the mineralisation of nitrogen from the pulp mill sludges in more detail, and to compare the effects of the sludges on crop yields with and without additional mineral nitrogen.

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Appendix 1. Details of the crop stand types, i.e. main plots, in the field experiment for pulp mill sludge

	Species, varieties, sowing densities (viable seeds m^{-1} or kg ha^{-1}), sowing date – harvesting date of the cereal and undersown and catch crops		
Stand type	Season 2015	Season 2016	Season 2017
Sole cereal		Spring wheat 'Anniina' 650 m^{-1} + 650 m^{-1} 7May(26 May) – 31 August 2016	Spring oat 'Obelix' 500 m^{-1} 10 May – 5 September 2017
Undersown cereal	Ryegrass 'Meroa', 20 kg ha^{-1} 12 May 2015 – 31 August 2015	'Anniina' as the sole cereal	'Obelix' as the sole cereal
Cereal with catch crop		'Anniina' as the sole cereal and ryegrass 'Meroa',21.3 kg ha^{-1} 11 September 2015 – 31 August 2016	'Obelix' as the sole cereal

Appendix 2. Results of Tukey's pairwise post hoc tests comparing yields between different fertiliser treatments. The estimate shows the difference between the treatments when the mean of the treatment in the 2nd column is subtracted from the mean of the treatment in the 1st column.

Pair of fertilisers compared		Wheat (2016)			Oat (2017)		
		Estimate	SE	p	Estimate	SE	p
Mineral	CPMS A	106.4	85.5	0.813	−81.6	103.4	0.968
	CPMS B	226.2	85.5	0.108	−225.7	103.4	0.266
	LPMS A	294.6	85.5	0.015 *	−173.6	103.4	0.553
	LPMS B	183.9	85.5	0.282	−149.7	103.4	0.698
	Zero-control	811.4	87.5	0.000 ***	1225.7	103.4	0.000 ***
Zero-control	CPMS A	−705.0	87.5	0.000 ***	−1307.3	103.4	0.000 ***
	CPMS B	−585.1	87.5	0.000 ***	−1451.4	103.4	0.000 ***
	LPMS A	−516.8	87.5	0.000 ***	−1399.3	103.4	0.000 ***
	LPMS B	−627.6	87.5	0.000 ***	−1375.4	103.4	0.000 ***
LPMS B	CPMS A	−77.4	85.5	0.943	68.0	103.4	0.986
	CPMS B	42.4	85.5	0.996	−76.0	103.4	0.976
	LPMS A	110.8	85.5	0.786	−23.9	103.4	1.000
CPMS B	CPMS A	−119.9	85.5	0.726	144.1	103.4	0.731
	LPMS A	68.4	85.5	0.966	52.1	103.4	0.996
LPMS A	CPMS A	−188.2	85.5	0.258	92.0	103.4	0.947

CPMS = composted pulp mill sludge; LPMS = lime-stabilised pulp mill sludge; SE = standard error; *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$