Agronomy Research **18**(X), xxx–ccc, 2020
https://doi.org/10.15159/AR.20.197

Effects of lake sediment on soil chemical composition, dehydrogenase activity and grain yield and quality in organic oats and spring barley succession

L. Edesi[1,*], T. Kangor[2], V. Loide[1], R. Vettik[1], I. Tamm[2], H.J. Kennedy[3], M. Haljak[2], Ü. Tamm[2], T. Võsa[1], K. Tamm[1], T. Talve[1] and E. Karron[1]

[1]Estonian Crop Research Institute, Department of Agrotechnology, Aamisepa 1, EE48309 Jõgeva alevik, Estonia
[2]Estonian Crop Research Institute, Department of Plant breeding, Aamisepa 1, EE48309 Jõgeva alevik, Estonia
[3]Estonian Crop Research Institute, Department of Development, Aamisepa 1, EE48309 Jõgeva alevik, Estonia
[*]Correspondence: liina.edesi@etki.ee

Abstract. In organic farming, it is important to maintain soil fertility with organic fertilisers; often organic compost, manure, or slurry is used. However, the effects of lake sediment in maintaining and improving soil fertility are less studied. The direct and residual effects of a one-time application of 50 t ha^{-1} or 100 t ha^{-1} of lake sediment were compared to an unfertilised control for oats *(Avena sativa)* (2015) followed by spring barley *(Hordeum vulgare)* in 2016, under organic farming conditions. Soil chemical composition, microbial activity in the 0–20 cm soil layer, grain yield, and grain quality were tested. The application rate, 100 t ha^{-1}, increased ($P < 0.05$) the soil organic carbon (SOC), the amount of mobile calcium (Ca), total nitrogen (N_{tot}), and boron (B) content in soil. Both application rates increased ($P < 0.05$) the amount of magnesium (Mg), copper (Cu), and manganese (Mn) content in the soil. The application rate had no effect on soil pH. Soil dehydrogenase activity (DHA) was higher ($P < 0.05$) at 100 t ha^{-1} than the control and the lower application rate. Both rates of lake sediment application significantly ($P < 0.05$) increased the grain yield and test weight for oats in 2015. Positive residual effects on spring barely yield only occurred in the 100 t ha^{-1} treatments in 2016. No residual impact of lake sediment was found on spring barely quality.

Key words: *Avena sativa*, *Hordeum vulgare*, lake sediments, organic farming, soil chemical composition, soil dehydrogenase activity.

INTRODUCTION

There are 1,534 natural, 525 reservoir, and 489 artificial lakes in Estonia, as of 2020 (Estonian Environmental Register, 2020). The main stages of development of Estonian lakes are dystrophic, with high levels of humic substances, and eutrophic, with high levels of nutrients (Kõiv, 2012). The result is that lakes become overgrown and a bog begins to develop. To stop this phenomenon, remediation plans have been drawn up for several lakes (Kahala lake, Jõepere lake, Elistvere lake etc.). According to these plans, the sediment would be partially removed from the lakes. It is not advisable to leave the removed sediment on the shore of the lake as most of the nutrients would drain back into the lake. In addition, depending on the lake, the amount of sediment may be too much for the shoreline to accommodate, for example, at lake Kahala about 12.07 million m^3 of sediments was removed. Therefore, the sediments recovered during the restoration process must be placed somewhere else (Metsur et al., 2015).

In organic farming, it is important to maintain soil fertility, but only via organic methods. In addition to other organic fertilisers, such as organic compost, manure, or slurry, the use of lake sediments could be also a possible method of maintaining and improving soil fertility.

Lake sediment (sapropel) rich in organic matter and minerals are formed from different organic compounds, such as the remains of aquatic plants and animals (Stankevica et al., 2016). Lake sediments are recommended for use on soils with lighter texture, where fertilisation effects occur more quickly (Kalmet et al., 1996).

Several studies on lake sediments have been published in nearby countries – other Baltic countries such as Latvia and Lithuania (Baksiene, 2009; Baksiene & Asakaviciute, 2013; Grantina-Ievina et al., 2014; Baksiene et al., 2015), Finland (Salonen et al., 2001), and Russia (Bogush et al., 2013). Positive effects on soil chemical, physical (Baksiene, 2009; Baksiene & Asakaviciute, 2013), and microbial properties (Grantina-Ievina et al., 2014; Hristeva & Bozhinova, 2017) have been found from sapropel application. Some studies show that fertilisation with lake sediments increases crop yields (Baksiene, 2004; Baksiene, 2009; Baksiene & Asakaviciute, 2013). However, Naumova and her colleagues (2017) found no effect of lake sediments application on yields.

At the same time, there may be some risks associated with using lake sediment as an organic amendment. Rapid industrialization and urbanization have led to a high accumulation of heavy metals in lake sediments, mainly originating from industrial discharge and waste from municipal activities (Li et al., 2012). Due to their toxicity, persistence, and bioaccumulation, heavy metals pose a potential threat to ecological system and human health (Li et al., 2012). However, heavy metal content analyses of freshwater sediment in Poland (Tylmann et al., 2011), Lithuania (Kruopiene, 2007), and Latvia (Stankevica et al., 2012) showed that the concentrations in sediment were generally low.

To our knowledge this is the first study in Estonia to examine the effects of lake sediment on soil chemical and microbial properties and on cereal yield and quality when used as an organic fertiliser in organic agriculture. The objective of this study was to assess the soil chemical composition, soil microbial activity, grain yield and quality of oats and spring barley when fertilised with various rates of lake sediment in organic farming conditions.

MATERIALS AND METHODS

Field experiment and treatments

The field experiment was conducted at the Estonian Crop Research Institute (ECRI) in Jõgeva (58°45'N, 26°24'E) during 2015–2016. The field trial was arranged as randomized plots of 10.5 m^2 with six replications. The trial area was already under organic farming cultivation. The soil of the experimental field is classified as *Calcaric*

Cambic Phaeozem (Loamic) clay loam soil (WRB, 2015). The initial soil chemical composition in spring 2015 was as follows: pH_{KCl} 7.4, P 47.4 mg kg^{-1}, K 101.0 mg kg^{-1}, Ca 4884.1 mg kg^{-1}, Mg 86.8 mg kg^{-1}, Mn 53.3 mg kg^{-1}, Cu 1.9 mg kg^{-1}, B 0.6 mg kg^{-1}, N_{tot} 0.2% and SOC 1.9.

Two fertiliser rates were tested: 50 t ha^{-1} and 100 t ha^{-1} of lake sediments (Table 1). The control had no fertiliser. No fertiliser was used in 2016 in order to measure the residual effects of the lake sediments fertiliser.

Table 1. Dry matter (DM), organic matter (OM), and amount of main nutrients in lake sediment applied in May 2015

Lake sediment, t ha^{-1}	DM, t ha^{-1}	OM, t ha^{-1}	N_{tot} (kg ha^{-1})	P_{tot}	P^M	K_{tot}	K^M	Ca	Mg	Mn	Cu	B	Fe^M
50	13.6	3.5	62	37.7	0.3	34.8	3.5	1,301	59	15	0.1	0.4	7.9
100	27.1	7.0	125	75.3	0.6	69.7	7.0	2,602	118	30	0.2	0.8	15.7

^{M}Mehlich 3 method.

In the first year (2015), the lake sediment was applied and ploughed into the soil before sowing the oat seeds. The sowing rate of oat var. *Eugen* was 600 seeds per m^2. In the second year (2016), when the residual effect of lake sediments was studied, 500 seeds per m^2 of spring barley var. *Maali* were sown. Both crops were sown at the optimal sowing time for eastern Estonia (the first week of May) with a Pöttinger sowing machine. In both years at growth stages 13–14 on the Biologische Bundesan-stalt, Bundessortenamt and CHemical Industry (BBCH) scale, harrowing was used to control weeds (Meier, 2001). All plots were harvested in August with a Hege combine harvester.

Soil and lake sediment sampling and analyses

Soil samples (approximately 0.5 kg) for chemical and soil dehydrogenase activity (DHA) analyses were taken from each treatment in six replications from the 0–20 cm layer with a 16 mm auger. Soil samples were taken in the spring before lake sediment application in 2015 and in the fall at harvest in 2015 and 2016. Additionally, soil samples were taken one month after the lake sediment application to analyse soil DHA. The chemical composition of lake sediment was analysed before application.

For soil chemical properties the following analyses were carried out: pH_{KCl}–ISO 10390; P, K, Ca, Mg, Mn – Mehlich 3 (Mehlich, 1984); N_{tot} – ISO 13878; B – Berger & Truog method; SOC – ISO 10694. Lake sediments were characterized for different parameters: dry matter content (DM) –gravimetric method; organic matter content (OM) – GOST 27980-88; N_{tot} – Kjeldahl method; pH_{KCl} – GOST 27979–88; P_{tot}, K_{tot}, Ca, Mg – PMK–JJ–4C; Mn, Cu, B– PMK–JJ–1A; available P, K and Fe – Mehlich 3. The soil and lake sediment chemical analyses were determined in an accredited laboratory at the Estonian Agricultural Research Centre.

Soil samples for DHA analyses were sieved (2 mm) and stored at 4 °C until they were analysed in ECRI's laboratory. Measurement of soil DHA were based on methods from Tabatabai (1982). Soil samples (5 g) were incubated at 30 °C for 24 h in the presence of an alternative electron acceptor (triphenyltetrazoliumchloride). The red-tinted product, triphenylformazan (TPF), was extracted with acetone and measured in a spectrophotometer (BioPhotometer plus).

Crop yield and quality

The grain from each plot was dried, cleaned and weighed separately. Grain yield was calculated at 14% moisture content. Grain quality characteristics such as thousand-kernel weight (TKW) (g), test weight (g L^{-1}), and protein content (%) were measured in ECRI's laboratory. TKW were measured by the ISTA method, test weight by an automatic grain analyser (Infratec 1241Analysis), protein content by the near-infrared method (NIR) using an XDS Rapid Content Analyser (Foss, Cheshire, UK) and a Monochromator (NIR).

Phenological growth stages were determined according to BBCH identification keys for cereals. Number of ears per m^2 was determined at BBCH 77–79.

Meteorological data

Meteorological data were obtained from a field meteorological weather station (Metos Compact) located at Jõgeva, close to the trial site. The meteorological data of the month is divided into three parts (I, II, III). I – the first 10 days of a month, II – the middle 10 days of a month and III – the last 10 days of a month.

Data from each year were different (Figs 1, 2). The average air temperature and precipitation of the 2015 growing period was similar to the long-term average (1922–2015) of the same period, though there were some drier stretches. The period from May II to June III (tillering, stem elongation), there was less precipitation which caused drought conditions for the oat plants. The second drier period was prior to harvesting (grain filling) through harvest, from July III to the end of August. Oats were harvested August 27.

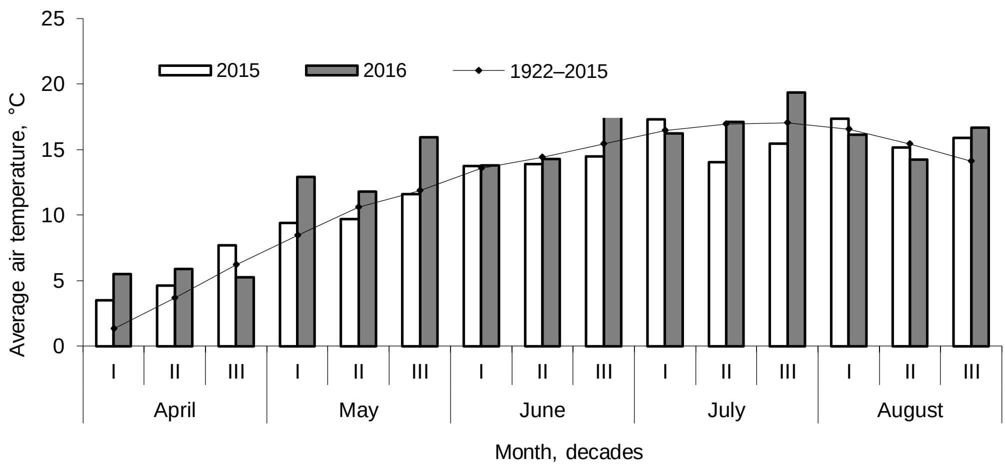

Figure 1. Average air temperature during growing periods of 2015–2016 and long-term average (1922–2015).

In 2016, the average air temperature during the growing period was somewhat higher than in 2015 and there were extreme precipitation fluctuations. May was very dry with only 4 mm of rain. During the same time, the average temperature was high and drought conditions occurred. The large amount of precipitation (120 mm) at the end of June saved the barley yield. Barley was harvested August 18.

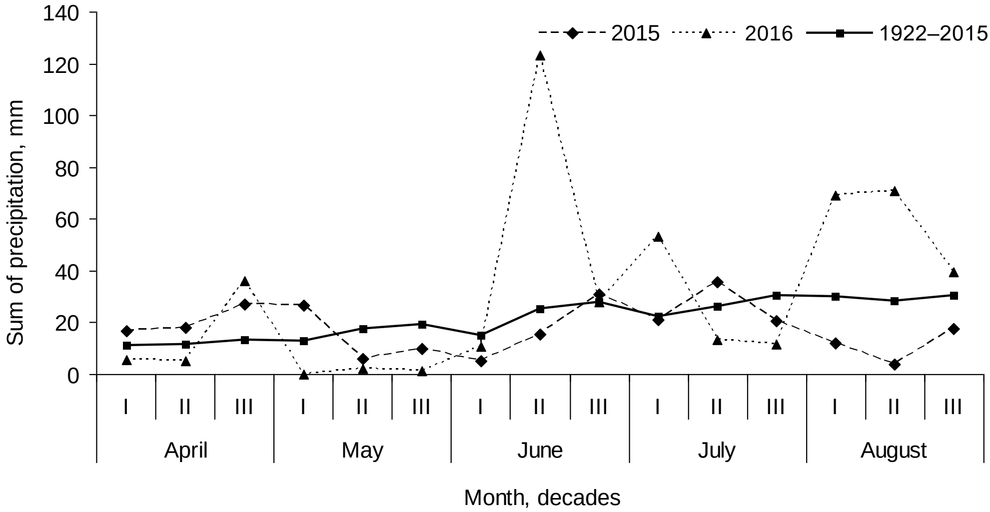

Figure 2. Sum of precipitation during growing periods of 2015–2016 and long-term average (1922–2015).

Statistical analyses

One-way ANOVA was used to test the effect of lake sediment on soil chemical properties, microbial activity, and grain yield and quality ($n = 6$) of oats and spring barley. In case of significant effects, differences between treatments were tested post-hoc using the *Tukey-Kramer (HSD) test*. The statistical analyses were performed using the *JMP 5.0.1.2* software.

RESULTS AND DISCUSSION

Soil chemical composition

The lake sediment application rate of 100 t ha^{-1} had significant direct and residual effects on some of the soil agrochemical parameters, while minor or no effect was found at the 50 t ha^{-1} rate (Table 2). In 2015, the use of lake sediment at 100 t ha^{-1} significantly ($P < 0.001$) increased the SOC content of the soil. Similar results were found by Baksiene and Asakaviciute (2013); they reported higher humus content in soil fertilised with a rate of 40 t DM ha^{-1} of lake sediment. Lake sediment (sapropel) is rich in organic matter and minerals are formed from different organic compounds, such as the remains of aquatic plants and animals (Stankevica et al., 2016). The proportion of organic matter in the lake sediment applied was 7.0 t ha^{-1} OM out of 100 t ha^{-1} lake sediment (Table 1). The second year showed that the residual effect of both sediment treatments on SOC was noticeable, but not significant.

The use of lake sediment at a rate of 100 t ha^{-1} significantly ($P = 0.002$) increased the amount of available Ca in the soil since a considerable amount (2,602 kg ha^{-1}) of Ca was applied in the lake sediment (Table 1). The soil pH was neutral before (7.4) and application of lake sediment did not change the soil acidity. Baksiene and Asakaviciute (2013) also found no effect of various rates of lake sediment application (10, 20 and 40 t DM ha^{-1}) on soil pH.

The content of Mg, Cu, and Mn in the soil was significantly influenced by the use of lake sediment (Table 2). Significantly ($P < 0.001$) higher N_{tot} and B content was found in the 100 t ha^{-1} treatment. In the case of Mn and B, the soil levels were quite low before the application of lake sediment and remained low afterwards.

Table 2. The average agrochemical properties of the 0–20 cm soil layer in fall 2015 and 2016

Treatment	Year	pH_{KCl}	SOC, %	N_{tot}, %	P	K	Ca	Mg	Cu	Mn	B
					mg kg^{-1}						
Control	2015	7.40^{a}	1.65^{b}	0.12^{c}	44.5^{ab}	114.8^{a}	4,037.3^{b}	75.3^{c}	1.70^{c}	49.5^{b}	0.72^{b}
50 t ha^{-1}		7.40^{a}	1.75^{b}	0.13^{b}	41.3^{b}	97.8^{b}	4,527.8^{b}	79.3^{b}	1.88^{b}	60.3^{a}	0.74^{b}
100 t ha^{-1}		7.40^{a}	1.98^{a}	0.16^{a}	49.5^{a}	118.3^{a}	5,713.8^{a}	90.8^{a}	2.25^{a}	63.8^{a}	0.89^{a}
P value		*ns*	*<0.001*	*<0.001*	*0.008*	*0.004*	*0.002*	*<0.001*	*<0.001*	*0.004*	*<0.001*
Control	2016	7.30^{a}	1.65^{a}	0.13^{a}	52.5^{a}	125.5^{a}	4,465.5^{b}	100.0^{a}	2.05^{b}	60.0^{a}	0.65^{b}
50 t ha^{-1}		7.40^{a}	1.80^{a}	0.13^{a}	46.5^{a}	113.0^{b}	5,306.5^{ab}	95.5^{a}	2.05^{b}	73.5^{a}	0.66^{ab}
100 t ha^{-1}		7.35^{a}	1.85^{a}	0.14^{a}	51.5^{a}	125.5^{a}	,6539.0^{a}	95.0^{a}	2.35^{a}	73.0^{a}	0.74^{a}
P value		*ns*	*ns*	*ns*	*ns*	*0.035*	*0.019*	*ns*	*0.037*	*ns*	*0.043*

Different letters indicate significant differences between treatment means ($n = 6$) (*Tukey-Kramer HSD test*, $P < 0.05$).

The sediment application had no effect on P and K content in soil. It could be because the total P and K content of the lake sediment at a rate 100 t ha^{-1} was 75.3 and 69.7 kg ha^{-1} of which only 0.6 and 7.0 kg ha^{-1}, respectively, was in plant available form, according to the Mehlich 3 test (Table 1). In iron-rich sediments, if the ratio of Fe to P is greater than 15, P will be unavailable to plants because oxidized iron ($FePO_4^{3-}$) is capable of binding all the dissolved P, under aerobic conditions (Jensen et al., 1992, Heinsalu et al., 2003). The soluble Fe to P ratio of the sediments used in the field trial was over 20.

Based on the second year soil data, a significant residual effect of lake sediments occurred only in case of Ca, Cu and B content at the 100 t ha^{-1} application rate with no significant residual effects at the 50 t ha^{-1} application rate.

Soil dehydrogenase activity

One month after lake sediment application, in June 2015, the soil DHA was significantly ($P < 0.001$) higher in the 100 t ha^{-1} treatment compared to the control and 50 t ha^{-1} treatment (Fig. 3). In fall 2015, the soil DHA remained significantly ($P = 0.003$) higher in the 100 t ha^{-1} treatment compared to the 50 t ha^{-1} treatment and the control. Compared to the control, the significantly ($P = 0.0204$) positive impact on soil DHA continued to be noticeable the following spring (2016). However, by fall 2016 the soil DHA of all treatments had returned to the pre-treatment level. The lake sediment application had no statistically significant effect on soil DHA in the 50 t ha^{-1} treatment throughout the experimental period.

The significant effect of the highest rate of lake sediment application on the soil DHA was probably caused by the higher SOC and nutrient content in this treatment (Table 2). It has been found that freshwater sapropel contains high levels of aerobic heterotrophic bacteria and yeasts (Grantina-Ievina et al., 2014). In addition, in 2015 there were extraordinarily dry periods in the two months prior to lake sediment application which consequently reduced soil moisture content (Fig. 2). At the same time, a large portion of the 100 t ha^{-1} of lake sediment applied was water (about 72.9 t ha^{-1}, equivalent to 7.29 mm of precipitation). A negative effect of drought on the size and activity of the soil microbial biomass was found by Hueso et al, (2012), while Siebert et al, (2019) found that soil microbial activity and biomass in grasslands were not affected by drought.

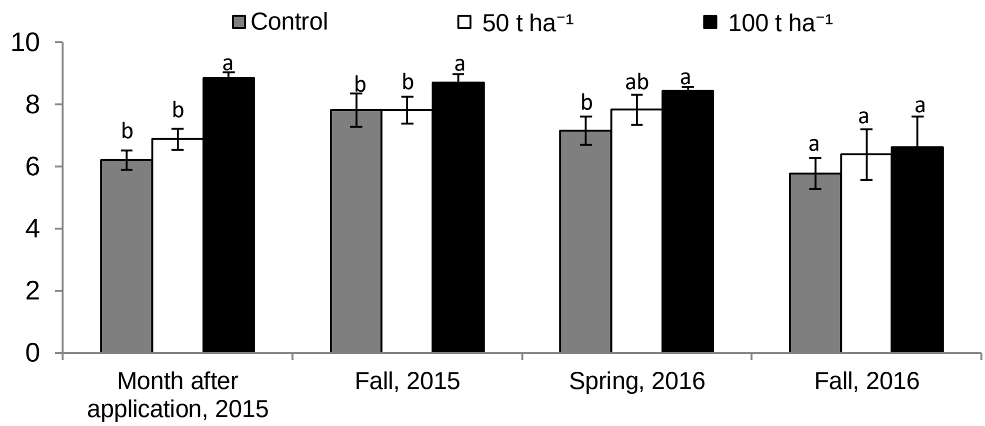

Figure 3. Soil dehydrogenase activity (DHA, TPF µg g^{-1} h^{-1}) in the 0–20 cm layer in 2015 and 2016. Different letters indicate significant differences between treatment means ($n = 6$) (*Tukey-Kramer HSD test*, month after application, $P < 0.001$; fall 2015, $P = 0.003$; spring 2016, $P = 0.0204$; fall 2016, $P > 0.05$).

Although the effect of lake sediment specifically on soil microbiological activity has been little studied, more generally there are many studies which have shown a strong positive relationship between soil microorganisms and organic fertilisers. Organic amendments such as manure provide a direct source of C for soil organisms (Bünemann et al., 2006; Fliessbach et al., 2007). Knapp et al., (2010) found that the compost amendments impact the soil microbiota and leave a distinct imprint on the soil.

Grain yield and quality

The first-year data showed that there was significant ($P = 0.005$) direct effects on oat yield from fertilisation with lake sediment. Compared to the control yield (4,353 kg ha^{-1}), both treatments increased oat yield; the additional yield was 417 kg ha^{-1} for the 50 t ha^{-1} treatment and 974 kg ha^{-1} for the 100 t ha^{-1} treatment (Table 3). The first year data showed that even the lowest rate of lake sediment application significantly increased the yield compared to the control. Similar results were found by Baksiene (2004), Baksiene & Asakaviciute (2013), and Kiani et al. (2018); however, the magnitude of extra yield depends on the

Table 3. Direct effect of lake sediment fertiliser on grain yield and quality characteristics of oats in 2015

Treatment	Yield, kg ha^{-1}	Plant height cm	Test weight, g L^{-1}	TKW, g	Protein content, %
Control	4,353^{b}	91^{b}	533^{b}	39.4^{b}	9.9^{a}
50 t ha^{-1}	4,770^{ab}	93^{ab}	537^{ab}	38.9^{b}	10.0^{a}
100 t ha^{-1}	5,327^{a}	97^{a}	538^{a}	41.7^{a}	9.2^{b}
P value	*0.005*	*0.007*	*0.013*	*0.001*	*0.008*

Different letters indicate significant differences between treatment means ($n = 6$) (*Tukey-Kramer HSD test*, $P < 0.05$).

crop species and its nutritional requirements. Plants require nutrients for their growth and development. In an organic farming system, the available amount of nutrients is usually limited. An adequate supply of nutrients for oats results in taller plants and more aboveground biomass (Daugviliene et al., 2014; Baksiene et al., 2015; Kiani et al., 2018). Oat plant height was significantly (P = 0.007) higher in the 100 t ha^{-1} treatment (97 cm) than in the 50 t ha^{-1} treatment (93 cm) and in control (91 cm). Despite this, no significant increase was found in the number of productive tillers when using lake sediment as fertiliser (data not shown). As known, the number of productive tillers, TKW and the number of kernels per ear or panicle determine cereal yield.

In the second year, when the residual effects of lake sediment were studied, barley yield was significantly (P = 0.023) higher in the plots where the highest rate of lake sediment (100 t ha^{-1}) was applied. The additional yield was 359 kg ha^{-1} (Table 4).

The barley plants grew significantly (P = 0.023) higher in the 100 t ha^{-1} plots as well (Table 4). However, the yield in the 50 t ha^{-1} plots was the same as in the control plots. As demonstrated, taller barley plants and significant additional yields were obtained, probably due to higher organic matter content and other nutrients in the soil where the highest rate of lake sediment was applied the previous year. Obviously, the additional yield of both crops (2015 and 2016) where the highest rate of lake sediment was applied was supported by higher soil microbial activity. This is because soil microbiota plays an important role in productivity of agricultural crops as it is responsible for the biochemical degradation of organic matter and other chemicals in soil (Munnoli et al., 2010).

Table 4. Residual effect of lake sediment fertiliser on grain yield and quality characteristics of spring barley in 2016

Treatment	Yield, kg ha^{-1}	Plant height cm	Test weight, g L^{-1}	TKW, g	Protein content, %
Control	2,908^{b}	56^{b}	641^{a}	46.7^{a}	9.6^{a}
50 t ha^{-1}	2,873^{b}	57^{ab}	640^{a}	45.7^{a}	9.4^{a}
100 t ha^{-1}	3,266^{a}	60^{a}	645^{a}	46.2^{a}	9.4^{a}
P value	*0.011*	*0.023*	*ns*	*ns*	*ns*

Different letters indicate significant differences between treatment means (n = 6) (*Tukey-Kramer HSD test* P < 0.05).

Oat test weight increased significantly (P = 0.013) in both the 50 t ha^{-1} and 100 t ha^{-1} treatments. TKW only increased (P = 0.001) in the 100 t ha^{-1} treatment. Kernel weight is one of the most important components affecting yield. This research revealed that organic sediment does not always have positive effects on grain quality characteristics. There was no effect on oat protein content in the 100 t ha^{-1} treatment, but in the 50 t ha^{-1} treatment the protein content significantly (P = 0.008) decreased so the effect of fertilisation was negative compared to the control. Organic farming often has a lack of nutrients. This is a crucial aspect to achieve sufficient protein content of cereals (Bilsborrow et al., 2013; Tamm et al., 2016).

There were no residual effects of lake sediment on barley grain quality characteristics in the second year (2016).

CONCLUSIONS

The rate of lake sediment applied had significant effects on soil chemical composition, soil dehydrogenase activity, as well as on grain yield and quality, with responses being strongest in the 100 t ha^{-1} treatment. The 100 t ha^{-1} treatment increased the amount of mobile Ca and B content in soil the first year. A residual effect was seen in the soil Ca, Cu and B content. Both application rates (50 and 100 t ha^{-1}) increased the N_{tot}, Mg, Cu, and Mn content in the soil the first year but had no effect on soil pH or P and K content. The higher application rate increased the SOC content, which could be a reason why soil DHA was higher in 100 t ha^{-1} treatment. Positive effects on soil DHA could be also due to the addition of a large amount of water along with the sediment.

The application of lake sediment increased grain yield, test weight, and thousand-kernel weight of oats in the first year. However, there were only small residual effects the following year. Barley yield was only positively impacted in the 100 t ha^{-1} treatment.

To use lake sediment as an organic fertiliser the ratio of Fe to P in the sediment should be considered in order to avoid a plant available P deficit in the soil. In order to recommend using lake sediment as an organic fertiliser to farmers, further research is needed to evaluate and avoid the risks of contaminating soils with heavy metals.

ACKNOWLEDGEMENTS. This research was supported by National Programme 'Agricultural Applied Research and Development Programme for 2015–2021'. We are also grateful to Laine Keppart for providing us the weather data.

REFERENCES

Baksiene, E. 2004. Effects of lake sediments on changes in sandy loam cambisol properties and on crop productivity. *Agronomy Research* **2**(2), 111–119.

Baksiene, E. 2009. The influence of lake sediments on the fertility of Cambisol. *Agronomy Research* **7** (Special Issue I), 175–182.

Baksiene, E. & Asakaviciute, R. 2013. The effects of organic lake sediments on the crop rotation yield and soil characteristics in Southeast Lithuania. *Applied Ecology and Environmental Research* **11**(4), 557–567.

Baksiene, E., Asakaviciute, R., Romanovskaja, D., Tripolskaja, L. & Razukas, A. 2015. The influence of lake sediments on sandy loam soil properties and crop yield. *Romanian Agricultural Research* **32**(1), 1–9.

Bilsborrow, P., Cooper, J., Tétard-Jones, C., Średnicka-Tober, D., Baranński, M., Eyre, M., Schmidt, C., Shotton, P., Volakakis, N., Cakmak, I., Ozturk, L., Leifert, C. & Wilcockson, S. 2013. The effect of organic and conventional management on the yield and quality of wheat grown in a long-term field trial. *European Journal of Agronomy* **51**, 71–80.

Bogush, A.A., Leonova, G.A., Krivonogov, S.K., Bobrov, V.A., Tikhova, V.D., Kondratyeva, L.M., Kuzmina, A.E. & Maltsev, A.E. 2013. Diagenetic transformation of sapropel from Lake Dukhovoe (East Baikal region, Russia). *Procedia Earth and Planetary Science* **7**, 81–84.

Bünemann, E.K., Schwenke, G.D. & Van Zwieten, L. 2006. Impact of agricultural inputs on soil organisms - a review. *Australian Journal of Soil Research* **44**, 379–406.

Daugviliene, D., Burba, A. & Baksiene, E. 2014. Changes of sandy loam Cambisol properties at application for calcareous sapropel and limestone. *Journal of Food, Agriculture and Environment* **12**(1), 1532–1536.

Estonian Environmental Register, 2020. Available at http://register.keskkonnainfo.ee/envreg/main#HTTP1iGilmPYdf6FWgbQfdhr2HWP6QJaPK accessed on 17.06.2020. (in Estonian).

Fliessbach, A., Oberholzer, H.-R., Gunst, L. & Mäder, P. 2007. Soil organic matter and biological soil quality indicators after 21 years of organic and conventional farming. *Agriculture, Ecosystems and Environment* **118**, 273–284.

Grantina-Ievina, L., Karlsons, A., Andersone-Ozola, U. & Ievinsh, G. 2014. Effect of freshwater sapropel on plants in respect to its growth affecting activity and cultivable microorganism content. *Zemdirbyste-Agriculture* **101**(4), 355−366.
Heinsalu, A., Vassiljev, J. & Veski, S. 2003. *Sediment properties of Lake Kääriku* /Kääriku järve lõunapoolse osa setete lasund ja omadused/. Institte of Geology at Tallinn University of Technology Report Series, 34 pp. (in Estonian).
Hristeva, T.H. & Radka P. Bozhinova, R.P. 2017. Microbiological characteristic of cinnamon pseudopodzolic soil (Planosol) at using of Black sea deep-water sediments (Sapropels). International *Journal of Current Microbiology and Applied Sciences* **6**(4), 125–133.
Hueso, S., García, C. & Hernández, T. 2012. Severe drought conditions modify the microbial community structure, size and activity in amended and unamended soils. *Soil Biology and Biochemistry* **50**, 167−173.
Jensen, H.S., Kristensen, P., Jeppesen, E. & Skytthe, A. 1992. Iron: phosphorus ratio in surface sediment as an indicator of phosphate release from aerobic sediments in shallow lakes. In *Sediment/Water Interactions,* Springer, Dordrecht, pp. 731–743.
Kalmet, R., Kanger, J., Kevvai, L., Kevvai, T., Kuldkepp, P., Kärblane, H., Raudväli, E. & Turbas, E. 1996. Mineral fertilisers. *Handbook of plant nutrition and fertilisation* /Mineraalväetised. Taimede toitumise ja väetamise käsiraamat/. H. Kärblane (Eds.), Estonian Ministry of Agriculture, Tallinn, 284 pp. (in Estonian).
Kiani, M., Simojoki, A., Tammeorg, O. & Tammeorg, P. 2018. Impacts of lake sediment reuse on plant growth and soil properties in the field. 21st World Congress of Soil Science in Rio de Janeiro, Brazil in August 12–17 (poster presentation). Available at https://researchportal.helsinki.fi/en/publications/impacts-of-lake-sediment-reuse-on-plant-growth-and-soil-propertie accessed 17.06.2020.
Knapp, B.A., Ros, M. & Insam, H. 2010. Do composts affect the soil microbial community? In: Insam H, Franke-Whittle I, Goberna M (Eds.), *Microbes at work*. Springer, Berlin, pp. 271–291.
Kruopiene, J. 2007. Distribution of Heavy Metals in Sediments of the Nemunas River (Lithuania). *Polish Journal of Environmental Studies* **16**(5), 715–722.
Kõiv, T. 2012. Development of the Estonian lakes /Eesti järvede arenguteed/. Available at http://lakeontogeny.weebly.com/eesti-jaumlrvede-arenguteed.html accessed on 11.06.2015. (in Estonian).
Li, H.B., Yu, S., Li, G.L., Liu, Y., Yu, G.B., Deng, H., Wu, S.C. & Wong, M.H. 2012. Urbanization increased metal levels in lake surface sediment and catchment topsoil of waterscape parks. *Science of the Total Environment* **432**, 202–209.
Meier, U. 2001. Growth stages on mono- and dicotyledonous plants. BBCH Monograph 2. Federal Biological Research Centre for Agriculture and Forestry. Available at https://www.politicheagricole.it/flex/AppData/WebLive/Agrometeo/MIEPFY800/BBCHengl2001.pdf accessed 19.02.2019.
Metsur, M. & Vreimann, T. 2015. A remedial action plan for the lake Kahala, the draft environmental impact assessment report /Kahala järve tervendamise insenertehnilise tegevuskava keskkonnamõju hindamise aruande eelnõu/. http://www.keskkonnaamet.ee/public/Kahala_KMH_aruande_eelnou.pdf accessed on 24.08.2015. (in Estonian).
Mehlich, A. 1984. Mehlich 3 soil test extractant a modification of Mehlich 2 extractant. *Communications in Soil Science and Plant Analysis* **15**, 1409–1416.
Munnoli, P.M., Teixeira da Silva, J.M. & Bhosle, S. 2010. Dynamics of the Soil Earthworm-Plant Relationship: A Review. *Dynamic Soil, Dynamic Plant* **4**(Special Issue), 1–21.
Naumova, N., Nechaeva, T., Smirnova, N., Fotev, Y. & Belousova, V. 2017. Effect of sapropel addition on selected soil properties and field tomato yield in south west Siberia. Asian *Journal of Soil Science and Plant Nutrition* **1**(3), 1–11.

Salonen, V-P., Varjo, E & Rantala, P. 2001. Gypsum treatment in managing the internal phosphorus load from sapropelic sediments; experiments on Lake Laikkalammi, Finland. *Boreal Enviroment Research* **6**, 119–129.
Siebert, J., Sünnemann, M., Auge, H., Berger, S., Cesarz, S., Ciobanu, M., Guerrero-Ramírez, N.R. & Eisenhauer, N. 2019. The effects of drought and nutrient addition on soil organisms vary across taxonomic groups, but are constant across seasons. *Scientific Reports* **9**. https://doi.org/10.1038/s41598-018-36777-3
Stankevica, K., Klavins, M. & Rutina, L. 2012. Accumulation of metals in sapropel. *Material Science and Applied Chemistry* **26**, 99–105.
Stankevica, K., Vincevica-Gaile, Z., Muter, O. & Klavins, M. 2016. Physiological response of bacteria consortium to the presence of intact and autoclaved freshwater sapropel (gyttja) derived in the eastern Latvia. In Mendez-Vilas, A. (ed.): *Microbes in the Spotlight: Recent Progress in the Understanding of Beneficial and Harmful Microorganisms*. Brown Walker Press, Boca Raton, 111–115. Available at: https://books.google.ee/books?id=s2C8DAAAQBAJ&pg=PA111&lpg=PA111&dq=sapropel+as+organic+fertiliser&source=bl&ots=dE0d84UMJs&sig=ACfU3U0WVu3BVSOIoN74BkasdJZIZeYxUw&hl=et&sa=X&ved=2ahUKEwjMyvC16MfgAhUyw8QBHV0xBWA4FBDoATAHegQIABAB#v=onepage&q=sapropel%20as%20organic%20fertiliser&f=false accessed on 19.02.2019.
Tabatabai, M.A., 1982. Soil enzymes. In: Page A.L., Miller R.H., Keeney D.R. (eds.). *Methods of Soil Analysis*. Part 2. American Society of Agronomy & Soil Science Society of America. Madison. Wisconsin, pp. 903–949.
Tamm, I., Tamm, Ü., Ingver, A., Koppel, R., Tupits, I., Bender, A., Tamm, S., Narits, L. & Koppel, M. 2016. Different leguminous pre-crops increased yield of succeeding cereals in two consecutive years. *Acta Agriculturae Scandinavica, Section B — Soil & Plant Science* **66**(7), 593–601.
Tylmann, W., Łysek, K., Kinder, M. & Pempkowiak, J. 2011. Regional Pattern of Heavy Metal Content in Lake Sediments in Northeastern Poland. *Water, Air, & Soil Pollution*. **216**, 217–228.
WRB, 2015. World reference base for soil resources 2014, update 2015. International soil classification system for naming soils and creating legends for soil maps. *World Soil Resources Reports* **106**, FAO, Rome, 203 pp.