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Effects of Long-Term Fertilization and Weather on Soil Properties and Spring Barley Yield

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Keywords: environmental safety, leaching, organic and chemical fertilizer, organic carbon, soil phosphorus.

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Effects of Long-Term Fertilization and Weather on Soil Properties and Spring Barley Yield

V. Loide [α] & L. Edesi [σ]

Abstract- The purpose of the experiment was to determine long-term fertilization and the effects of weather on the soil properties and spring barley yields. A long-term field experiment—with crop rotations of potatoes (hemp oil from 2017), spring barley, spring barley with red clover (undersown), and red clover was established in 1960 Kuusiku, Estonia. Different barley varieties was used over the experimental period. With except the spring barley variety 'Anni', which was tested from 1995–2019.The experiment has three fertilizer treatments: the moderate dose of fertilization (NPK1),double NPK1 (NPK2), and moderate fertilization with farmyard manure (NPK1 + FYM). After harvest, the soil samples were collected from 0–0.2 m of topsoil and 0.2–0.4 m of subsoil from each plot, using a soil drill.

During the experimental period, soil organic carbon content increased from 1.3% (NPK1) to 1.9% and 2.5% when using mineral fertilizers (NPK2) and NPK1 + FYM, respectively. The use of manure increased soil microbial biomass by 9.7%, and the use of mineral fertilizers decreased by 23%. More nutrients—especially phosphorus, potassium, and magnesium—moved from the topsoil to the subsoil with the use of manure (NPK1 + FYM) than with the of mineral fertilizer alone (NPK2).

Phosphorus leaching was higher with manure (22% in subsoil) compared to that with mineral fertilizer. Of the period studied, 28% was under drought, which caused 60% spring barley yield loss and thus increased the risk of leaching of unused nutrients.

Keywords: environmental safety, leaching, organic and chemical fertilizer, organic carbon, soil phosphorus.

I. Introduction

Long-term field experiments with fertilizers make it possible to examine not only the yield of crops but also the impact of long-term fertilizer uses on soil properties, sustainability, and the environment. In soil, processes occur very slowly, and the results of various factors can only be evaluated in long-term experiments. Specifically, long-term fertilizer experiments are vital tools to examine the sustainability of modern intensive cropping systems and provide valuable information regarding the impact of continuous fertilizer applications on soil health and crop productivity (Meena et al., 2017). Microorganisms are crucial in soils, being responsible for nutrient cycling and fixation, organic matter decomposition, and biological suppressiveness. Therefore, soil stability and functioning in agriculture are closely related to its microbiological diversity and activity (Griffiths & Philippot, 2013). Soil microorganisms are also sensitive to changing environmental conditions, which makes them good indicators of soil quality(Griffiths & Philippot, 2013; Schloter et al., 2018).

In several long-term studies, considerable attention is to the accumulation of available phosphorus(P) in soil, its movement to the lower soil horizons, and its leaching, and the elucidation of conditions conducive to such a phenomenon(Rubæk et al., 2013; Zicker et al., 2018). Manure is one of the sources of phosphorus, the overuse of which may saturate the soils with P. In Estonia, 50% of the P used in crop production comes from manure (ES…). Excess phosphorus in the soil has caused the eutrophication of water bodies, including the Baltic Sea in Europe. There is an increasing focus on protecting water bodies from eutrophication(Carpenter, 2008).

Weather conditions, i.e., temperature and precipitation, also change over long periods, affecting crop yields, nutrient uptake, accumulation, and leaching. These issues have been studied by many authors on the basis of long-term experiments (Körschens *et al*., 2013).

The aim of the experiment was to gain new knowledge as follows. 1) Effects of long-term mineral fertilizers, and in particular manure, on topsoil and subsoil properties and environmental safety. 2) The combined effect of air temperature and precipitation (hydrothermal effect) on the growth conditions of spring barley, on which nutrient consumption, yield and leaching of unused nutrients depend.

II. Materials and Methods

a) *Study site and soil*

This study was carried out based on data from an ongoing long-term crop rotation and fertilization experiment, which was established in 1960 by E. Talpsep at the Kuusiku experimental station of the ECRI (Estonian Crop Research Institute), Northern Estonia; longitude 58.977554, latitude 24.725849, and altitude 55 m) on light Sandy Loam Calcisols (IUSS 2015). The experiment was redesigned reconstructed in 1975 and 1995–1997. The data used in this study have predominantly been from 1995 onwards.

Crop rotation:- potato (*Solanum tuberosum*)/ oil hemp (*Cannabis sativa*; since 2017); – spring barley (*Hordeum vulgare*); – spring barley with under sown red clover (*Trifolium pratense*); – red clover. Barley varieties

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varied according to the variety representation in practice, except the spring barley variety 'Anni', which was tested from 1995–2019. All cultures were presented every year. The size of each trial plot was 98 m^2 (14 × 7 m).

Traditional agro technical measures were used: the soil was plowing to a depth of 0.22 m, and chemical plant protection measures were also taken. Mineral fertilizers were applied during soil tillage before sowing. Manure was applied by autumn plowing for the potato or oil hemp of the following year.

The experiment had three fertilizer treatments and five repetitions: a moderate dose of NPK (NPK1-control), double NPK1 (NPK2), and a moderate dose of fertilizer with farmyard manure (NPK1 + FYM). The fertilization dose is in Table 1. Cereal straw was returned to the soil by plowing. The applications of fertilizers, crop sowing (end of April), and harvesting was performed at the optimal time (August).

Table 1: Test fertilisation of crops in a long - term experiment (since 1960) in Kuusiku

Treatment	N:P:K kg ha^{-1} ,+ FYM*, t ha^{-1}			
	Crop rotation			
	Potato/hemp	S.barley u.show	Red clover	Spring barley
NPK1 (control)	90:27:116/35:0:0	40:8:30	-	80:16:60
NPK2	180:54:232/70:0:0	80:16:60	-	120:24:90
NPK1+FYM	90:27:116+60FYM/35:0:0+60 FYM	40:8:30	-	80:16:60

*- The nutrient content (kg t^{-1}) of manure (FYM): N (nitrogen), 2.8 kg^{-t}; P (phosphorus), 0.6 kg^{-t}; K (potassium), 4.7 kg^{-t}.

b) Soil sampling and analysis

After harvest, soil samples (1 sample consisted of 15 subsample) were collected from the topsoil, (0–0.2 m depth) and subsoil (0.2–0.4 m depth) layers from each using a soil drill. The soil samples were air-dried and sieved to <2 mm. The chemical properties of the soil samples were then determined in an accredited laboratory at the Agricultural Research Centre, Estonia, as follows: C_{org} (organic carbon), using the - sulfochromic method; pH_{KCl}, using the – ISO 10390:2005 methodology; available P, K, Ca, Mg, Al, and Fe, using the - Mehlich III extraction (Meh3) method (Mehlich, 1984). The determination was performed using the ICP-OES (Inductively Coupled Plasma Optical Emission Spectrometer). The total content of the elements P, K, Ca, and Mg: (P_{tot}, K_{tot}, Ca_{tot}, and Mg_{tot}) in the soil was determined using the EVS-EN 16170:2016methodology. Water-soluble phosphorus, P_{H2O}, in the soil was determined by using the EVS-EN ISO 11885:2009 methodology.

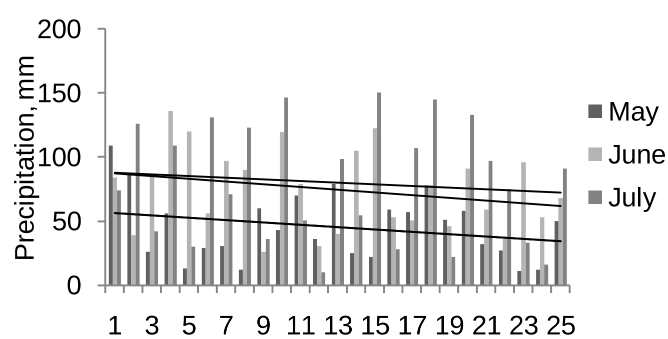
Soil samples (0.5 kg) for soil dehydrogenase activity (DHA) analyses were taken from the 0–0.2 m layer in three replications under the early and late spring barley cultivation in spring 2016. Soil samples for DHA analyses were sieved (2 mm) and stored at four °C until they were analyzed in the ECRI's laboratory. Measurements of soil DHA were based on methods by Tabatabai (1982). Soil samples (5 g) were incubated at 30 °C for 24 h in the presence of an alternative electron acceptor (triphenyltetrazolium chloride). The red-tinted product, triphenylformazan (TPF), was extracted with acetone and measured using a spectrophotometer.

c) Sampling and analysis of crop yields

Trial plot yield and dry matter determination, 32.5 m^2 (2.5 m × 13 m) of the crop was harvested, of which 1 kg was taken for analysis. The current study includes long-term research data from 1975–2019.

d) Calculation of the hydrothermal coefficient

Estonia is characterized by a transitional climate from maritime to continental. The average annual air temperature is 6.7 °C, and the average precipitation is 696 mm. The average annual water evaporation is less than the precipitation. Temperatures and precipitation were measured during the vegetation period (Fig. 1) using an automatic weather station near the experimental area. The conditions (Keppart et al., 2009) for plant growth and development are more characterized by the Seljaninov.



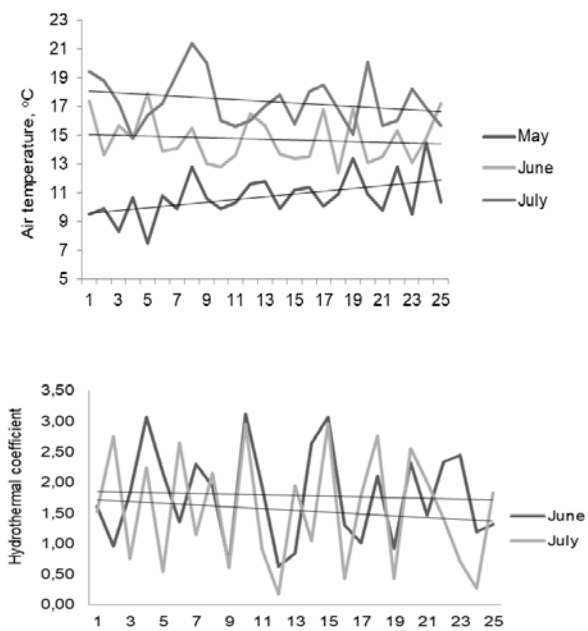


Figure 1: Characterization of the weather during the trial period 1–25 (1995–2019) in Kuusiku

Hydrothermal coefficient (HTC), also called conditional moisture balance, which takes into account the combined effect of temperature and precipitation. Plant stress is higher either in conditions of high temperature, and lack of water or conditions of lowtemperature and plentiful water. The hydrothermal coefficient (Kivi, 1998) was calculated using the sum of precipitation (P) and the sum of air temperatures (T) for the same period using the following formula (1):

$$HTC = \sum P / 0.1 \times \sum T_{day} \quad (1)$$

where $\sum P$ is- the sum of precipitation, and $\sum T_{day}$is- the sum of air temperatures.

e) Statistical analysis

The period was considered dry if the HTC is between 1.0–0.6 and very dry if the HTC is 0.5 or less (Keppart et al., 2009). If the HTC exceeds 2.0, the period was considered to be too wet for crop cultivation.

The correlation and standard deviation (SD) for yield, weather, and soil chemical properties were calculated. The likelihood of a difference between treatments was found at a level of 95% confidence in the $LSD_{0.05}$ (LSD; least significant difference) test.

III. Results and Discussion

a) Soil properties

This study (Tables 2, 3) showed that organic and mineral fertilizers had different effects on soil properties during long-term fertilization. Understandably, the use of manure increased the C_{org} content of the soil in the barn layer and also in the subsoil. Manure application also promoted soil microbiological activity (DHA) compared to the control test by 9.7%, while mineral fertilizer reduced by 23% (NPK1-control: 5.16; NPK1 + FYM: 5.66 and NPK2: 3.98 TPF µg/g/h; $LSD_{0.05}$: 0.72). From an environmental point of view, P deserves more attention. Additional P and K fertilizers were added in turn (every four years): P 51 and K 206 kg ha^{-1} in NPK2 test and 36 and 280 kg ha^{-1} in NPK1 + FYM test. Although less P was added with manure than with mineral fertilizer, the subsoil contained more P.

Table 2: Effect of long-term fertilisation on soil agrochemical parameters in 2019 in the top- and subsoil layers of the carbonate soil in Kuusiku

Treatment	C_{org}	pH_{KCl}	Content of soil elements							
			P		K		Ca		Mg	
	%		mg kg^{-1}	%	mg kg^{-1}	%	mg kg^{-1}	%	mg kg^{-1}	%
Content of soil available elements in the topsoil (0–0.2 m; *n*=20)										
NPK1-control	1.9	6.0	146	100	149	100	1850	100	64	100
NPK2	1.9	5.9	213	146	211	142	1810	98	68	106
NPK1+FYM	2.5	6.5	203	139	314	211	2350	127	131	205
$LSD_{0.05}$	0.17	0.22	25	-	48	-	205	-	22	-
Content of soil available elements in the subsoil (0.2–0.4 m; *n*=20)										
NPK1-control	1.1	6.0	56	100	88	100	1470	100	43	100
NPK2	1.4	6.1	125	223	152	173	1890	129	54	126
NPK1+FYM	1.9	6.4	152	271	306	348	1820	124	116	269
$LSD_{0.05}$	0.21	0.24	28	-	65	-	197	-	22	-
Content of soil total elements in the topsoil (0–0.2 m; *n*=205)										
NPK1-control	-	-	559	100	1581	100	3481	100	1741	100
NPK2	-	-	644	115	1608	102	3322	95	1708	98
NPK1+FYM	-	-	617	110	1662	105	3642	105	1728	99
$LSD_{0.05}$	-	-	22	-	51	-	279	-	42	-

Table 3: Correlative relationships between C_{org} and soil properties in the top- and subsoil layers of the carbonate soil in Kuusiku

Indicators	FYM	Min. fertiliser	C_{org}-topsoil	C_{org}-subsoil
C_{org}-topsoil	0.885**	-0.845**	-	-
C_{org}-subsoil	0.923**	-0.129	-	-
DHA	0.534	-0.845**	0.707*	-
pH_{KCl}	0.771**	-0.574	0.784**	0.628*
P	0.349	0.531	-0.069	0.635*
K	0.876**	-0.166	0.630*	0.929**
Ca	0.846**	-0.584*	0.836**	0.710**
Mg	0.933**	-0.437	0.810**	0.874**

$*p<0.05$; $**p<0.01$; $n=12$.

Organic matter plays a key role in the microbiological transformation of phosphorus compounds in soil and the promotion of plant phosphorus uptake (Richardson & Simpson, 2011). Organic substances are also an source of energy for the bacteria and fungi that break down manure. As a result of their activities, nutrients are released and become mobile and available to plants. However, the addition of mineral fertilizers hurt the biological activity of the soil. The positive interaction of organic manure and inorganic NP fertilizer on soil DHA was observed by Liu et al., (2010). The results of the present study clearly show that the amount of mineral fertilizer applied to the NPK2 treatment had a negative effect on the microbiological activity of the soil. This finding is supported by the Treseder (2008) review, where it was concluded that inorganic fertilizers suppress microbial biomass, with more evident effects in longer durations and with higher total amounts of N added. Some studies have shown that repeated applications of inorganic fertilizers decrease soil pH (Liu et al., 2012), which, in turn, can reduce nutrient availability and soil microbial biomass.

Plants absorb phosphorus from the soil primarily as orthophosphoric acid anions soluble in water or as weak organic acids. In this experiment (Table 4), the content of P_{H2O} in the soil increased 1.7–2 times, and that of P_{Meh3} increased 1.4–1.5 times in the NPK2 and NPK1 + FYM treatments as compared to the control (NPK1).

Typically, the proportion of water-soluble P compared to available P is relatively small, only 17–20%. Compared to the NPK1 experiment (Table 2), the P_{H2O} content in the NPK2 and NPK1 + FYM experiments increased significantly by 170 and 203% (respectively). Excess P in the subsoil, however, is dangerous to the hydrosphere.

Table 4: Water-soluble phosphorus content in the topsoil layer of the carbonate soil in 2020 in Kuusiku depending on fertilisation

Treatment	Indicators				
	P_{H2O} mg kg^{-1}	P_{Meh3} mg kg^{-1}	P_{H2O} % in P_{Meh3}	Rel. P_{H2O} %	Rel. P_{Meh3}, %
NPK1-conrol	7.1	144	20.3	100	100
NPK1+FYM	12.1	205	16.9	170	142
NPK2	14.4	222	19.5	203	154
$LSD_{0\cdot05}$	2.1	30.3	1.3	-	-

The association of organic matter with phosphorus retention and incorporation into soil has been described by several researchers. Pizzeghello et al. (2016) also found that mineral fertilization reduced P-sorption capacity by increasing the P content in soil and water samples, but to a lesser extent than that by manure. The outer surface of organic colloids is considerably larger than the outer surface of most other colloids and usually exceeds the corresponding value of clay minerals. At high pH, the cation exchange capacity of humus is significantly higher than that of clay minerals. The particles of organic matter, including manure, have a larger mass and thus occupy the free surface, and the free P in the soil-based solution leached with falling water.

Moreover, P leaching from soils with elevated P levels due to manure spreading is becoming an increasing concern as a source of eutrophication in streams, lakes, and the Baltic Sea region (Hooda et al., 2001; Lehmann et al., 2005; Schick et al., 2020). In a radio labelled orthophosphoric acid sorption experiment, Vanden Nest et al. (2016) found that soil P availability and leaching were associated with a decrease in orthophosphate sorption in farmyard manure-modified soils, which was not observed in compost-modified soils. Nobile et al. (2019) found that using one-tenth of an organic fertilizer increased soil pH and C_{org}, but at the same time decreased P sorption. Ten years of application of mineral fertilizers reduced soil pH, and increasing the P sorption. Hooda et al. (2001) found that 85 mg P kg^{-1} and 305 mg P kg^{-1} of the Olsen and Mehlich-3 extractable P values were predicted for 25% DSSP (DSSP stands for the degree of soil saturation with P). Soil saturation with P is likely to cause significant P losses to the environment. Saturation of the soil with P is caused by P unused by plants, which is one of the consequences of drought, and in case of heavy precipitation, P enters water bodies.

b) Dependence of yields on the weather

Spring barley yields (Table 5) did not differ between different fertilizer treatments but depended most on the weather. The weather conditions (Fig. 1) were very volatile. In our experiment, almost 1/3 (28%) of the years gave an average spring barley yield of 2.1–2.2 t ha^{-1}, 38% less than in the best years (48%). With the lost crop, an equivalent amount of fertilizer remains in the soil. The results of the correlation analysis ($p < 0.01$) showed that the spring barley yield was most positively affected by the June precipitation, and negatively by the high air temperature in July. However, given the air temperature and precipitation, HTC showed that spring barley yields currently depend on air temperature and precipitation in June and then in July. The highest spring barley yields were obtained when the HTC was close to 2.2 in June and July, which implies that the barley needs a relatively moist June-July. Earlier investigations suggested that cooler, cloudier, and rainy weather occurs in June and in early July (the period for stem elongation to grain head formation), which has a positive impact on grain yield. May is particularly critical for spring barley growth, which often has high air temperatures (rising trend) and little rainfall. Depending on the June and July rainfall, the plant will recover from drought damage or not. Previous studies have shown that crop species with powerful and widespread roots that can collect water and nutrients more widely are more resistant to weather conditions, resulting in higher yields (Dempewolf *et al*., 2014). Therefore, in the long run, one way to reduce the damage caused by water scarcity is to study the root system of the plant during the cultivation of the variety and its development during the growing season.

Table 5: Correlation between weather and spring barley yield in the years 1995–2019 in Kuusiku

Indicators	25 years average		Good harvest, weather (>5 t ha^{-1}, 10 y average)	Poor harvest weather (<4 t ha^{-1}, 7 y average)
	Correlative relationships	Results		
$Yield_{NPK1}$, kg ha^{-1}	-	4510	5460	3350
$Yield_{NPK2,}$ kg ha^{-1}	-	4540	5680	3480
$Yield_{NPK1+FYM}$ kg ha^{-1}	-	4590	5630	3540
Rel. $yield_{NPK1}$, %	-	100.0	100.0	100.0
Rel. $yield_{NPK2}$,%	-	100.7	104.0	103.9
Rel. $yield_{NPK1+FYM}$, %	-	101.8	103.1	105.7
Air temperature, °C; May	-0.401*	10.7	10.3	11.8
Air temperature, °C; June	-0.475*	14.7	13.8	15.1
Air temperature, °C; July	-0.775**	17.4	16.0	19.2
Precipitation, mm; May	0.013	45	46	45
Precipitation, mm; June	0.535**	77	92	49
Precipitation, mm; July	0.464*	80	109	60
HTC May	0.056	1.39	1.44	1.30
HTC June	0.632**	1.78	2.25	1.08
HTC July	0.528**	1.54	2.18	1.05

*$p<0.05$; **$p<0.01$; $n=25$.

Therefore, not only in terms of yield stabilization but also in terms of environmental safety, it is necessary to use more and more weather-resistant varieties. For more environmentally friendly use of manure, it is to monitor the properties of soil which leaching depends, such as soil saturation with P. The P in manure is released more slowly. Still in the case of imbalances, it is easily subjected to leaching. To reduce the negative impact of the weather on crop yields and environmental safety, it is recommended to use more reliable weather varieties and to limit fertilization in the year following the drought, especially P.

IV. Conclusions

The following were observed during the experimental period, (1) soil organic carbon content increased from 1.3– to 1.9% when using mineral fertilizers and from 1.3– 2.5% when using NPK1 + FYM. (2) The use of manure increased soil microbial biomass by 9.7%, and the use of mineral fertilizers decreased by 23%.(3) More nutrients — especially phosphorus, potassium, and magnesium — moved from the topsoil to the subsoil when manure was used than when mineral fertilizer was used. Phosphorus leaching was higher with manure (22% in subsoil) than with mineral fertilizer. (4) Of the period studied (25 y), 28% was affected by drought, which caused 60% spring barley yield loss and thus increased the risk of leaching of unused nutrients.

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