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# Efficiency of lime application on sod-podzolic soil in the north-western region of Russia

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**Abstract.** The article presents the analysis of the results of a long-term experiment on studying the effectiveness of the combination of the doses of lime and mineral fertilizers on sod-podzolic sandy loam soil in crop rotation in the Leningrad region. Research experiments are carried out in the six-field crop rotation. The data obtained in the course of long-term stationary field experiments are more reliable and accurate compared to the results of model experiments. The liming and long-term uses of mineral fertilizers affect the crop nutrition pattern and the migration capacity of substances in soils. The application of moderate doses of mineral fertilizers during soil liming increases the number of bacterial microflora. Liming significantly increases the nitrification capacity of the soil. Liming of strongly acidic sod-podzolic soils increases the amount of phosphorus and fertilizers the crops take from soil. Calcium, which is a part of phosphorus fertilizers, is essential for acid-sensitive crops. The optimal reaction level for crop development is not constant. In case of a good crops supply with nutrients, the optimal reaction level shifts to a more assiduous area. As a result, the knowledge of the process patterns occurring in the soil under the influence of anthropogenic agricultural activity was obtained. The data obtained are the key to control the soil evolution during its agricultural use.

## 1 Introduction

The study of anthropogenic influence on soils is an actual necessity of our times. In order to improve the methods of soil fertility conservation, control and forecast changes in arable soils, the necessity to study the regular patterns of changes in basic properties of agricultural soil is recognized [1–3]. The problem of the fertility reduction in acidic soils in various regions of the world has been recognized for a long period of time [4–10]. In acidic soils with pH < 5.5, the solubility of aluminum increases to toxic levels forming insoluble phosphates, which may severely limit the root system and reduce the plant growth [11–13]. The introduction of lime in agricultural soils has been widely used for a long period of time as a reclamation strategy aimed at improving plant nutrition [14–16]. Reasonable recommendations for the use of ameliorate and fertilizers can be given only on the basis of long-term experiments [17, 18].

The studies carried out in the form of a long-term field experiment and related studies in lysimetric, model and vegetation experiments were carried out. As a result, the knowledge about the regular patterns of processes occurring in the soil under the influence of human production activity was obtained [17, 18]. The comparison of the process results with characteristics of natural and fallow soils in the same soil-climatic conditions allows determining the agro-ecological consequences of human activity and finding ways to preserve and increase soil fertility [19].

Liming significantly increases the efficiency of mineral fertilizers introduced to acidic soils in the North-West region of Russia. Mineral fertilizers, in turn, have a strong influence on calcium loss from the soil and its reaction. The data obtained in the course of long-term stationary field experiments are more reliable and accurate compared to the results of model experiments.

There are soils of more than one hundred varieties within the agricultural lands of the Leningrad region [1, 20], but after grouping them, the source-based distribution of soils gives us the following picture (Table 1).

The granulometric composition of the soil is an important stable characteristic. It is associated with differences in water, thermal and biological regime of soils and their absorption capacity. This characteristic is one of the criteria determining the doses of mineral, organic fertilizers and lime, as well as the design of reclamation measures. The soil fertility also depends on the granulometric composition. All this makes the summary of soil distribution by granulometric composition (Table 2) important agronomic information.

Extreme gradations of granulometric composition in the Leningrad region (sands and clays) are of a limited distribution. This is a positive feature. Light-loamy soils are optimal for most crops. That is, long-term experiments of the Leningrad Research Institute Belogorka are carried out in typical agricultural landscapes, which are most

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common in our region. These fundamental experiments are important for controlling the soils evolution during their agricultural use.

**Table 1.** Ratio of soils in the Leningrad region is of different genesis, %

| Type of land | Sod-podzolic | Sod-podzolic gleic | Swamp-podzolic and swamp | Sod-carbonate | Sod-alluvial |
|---|---|---|---|---|---|
| Arable land | 52 | 23 | 10 | 13 | 2 |
| Pastures | 41 | 25 | 20 | 12 | 2 |
| Hayfields | 29 | 24 | 36 | 3 | 8 |

**Table 2.** Granulometric composition of agricultural soils in the Leningrad region (% of farmland area)

| Type of land | Sandy | Sandy loam | Light loamy | Loamy | Heavy-loamy |
|---|---|---|---|---|---|
| Arable land | 2.5 | 21.7 | 27.7 | 36.0 | 4.1 |
| Pastures | 2.3 | 17.9 | 29.6 | 34.5 | 4.6 |
| Hayfields | 2.4 | 15.6 | 21.3 | 29.4 | 3.5 |

## 2 Methods and objects

The experiment was carried out in 1981 on the experimental field of the Federal State Budgetary Scientific Institution Leningrad Research Institute of Agriculture Belogorka. Coordinates of the experiment – 59º21' North latitude; 30º08' East longitude. During the experiment sod-podzolic sandy slightly cultivated soil was used (Fig. 1). According to the A.G.Kachinskiy classification the granulometric composition of the soil used in the experiment is defined as the boundary between the sandy loam and the light loam (particle content >0.01mm – 82.78 %; <0.01mm – 17.22 %; <0.001mm – 5.31 %).During the experiment, the soil had the following agrochemical characteristics: pH in KS1 – 4.46; Ng – 4.33 mg-eq per 100 g; S – 4.5 mg-eq per 100g of soil; V – 50.9 %; mobile phosphorus – 200, exchange potassium – 125 mg/kg of soil; humus – 2.2 %.The experimental studies are carried out with a six-field crop rotation: 1- spring barley with the additional seeding of perennial grasses (clover + herd grass); 2 – annual grasses; 3 – 2-year grasses; 4 – winter rye; 5 – potatoes; 6- oats. The experiment scheme consists of six liming variants: 1 – without lime; 2 – 0.25 Ng liming; 3 – 0.5 Ng liming; 4 – 1.0 Ng liming; 5 – 2.0 Ng liming; 6 – 2.5 Ng liming. The lime was introduced at four levels of mineral nutrition: a – without fertilizers; b – medium presence; c – elevated presence; g – high presence. The initial doses of mineral fertilizers and the ratio of nutrients in the fertilizers used were calculated depending on the physiological characteristics of cultivated crops and the initial agrochemical soil characteristics. Since 2001, complex fertilizers have been introduced. The experiment has a four-fold repetition, the plot area is 7x10 = 70 $m^2$; the area of the experiment is 1.2 ha. Soil samples from the arable horizon are selected annually in autumn, deep samples – once in rotation. The laboratory studies of agrochemical soil indicators were carried out according to commonly accepted methods (Arinushkina E.V., 1970; Petersburgskiy A.V., 1968; Agrochemical methods of soil examination, 1975) and GOSTs (GOST 26951-86 – Soils) [20]. Standard methods of mathematical statistics were used for experimental data processing [20]. Based on the obtained materials, in order to determine ways to reduce the leaching of calcium and other substances from arable soils and to preserve soil fertility, the concept of creating environmentally-friendly mineral fertilizers was developed and experimentally examined.

## 3 Results and discussion

The greatest changes in soil pH KS1 occur during the first year after the lime application and remain unchanged from 3 to 6 years. During this period, along with the leaching of the bases, there is an interaction of soil with non-reacting lime, so in short-term experiments (up to 3 years) it is not possible to detect any significant impact of mineral fertilizers on the pH of the soil. Two years after the lime introduction, the content of free lime, which did not react with the soil, was from 10 to 64 % of the amount applied depending on the dose (Table 3).

**Table 3.** Influence of liming and mineral fertilizers on the content of free carbonates in sod-podzolic sandy soil two years after the lime administration

| In the presence of fertilizer | Dose lime, t $ha^{-1}$ | Content of lime which did not react with the soil ($CaCO_3$) | | |
|---|---|---|---|---|
| | | in mg per 100g of soil | t $ha^{-1}$ | in % of the administered dose |
| Fertilizer free | 0 | 0 | 0 | 0 |
| | 7.7 | 207±17.6 | 6.2 | 34 |
| | 18.3 | 207±17.6 | 6.2 | 34 |
| | 30.8 | 627±33.3 | 18.8 | 61 |
| N120P120K120 | 0 | 0 | 0 | 0 |
| | 7.7 | 77±8.8 | 2.3 | 30 |
| | 18.3 | 140±30.0 | 4.2 | 23 |
| | 30.8 | 657±42.5 | 19.7 | 64 |

When using mineral fertilizers without lime application in 4–5 years the pH of the soil becomes lower than during the control period. The bases are washed out by atmospheric precipitation together with mobile anions of fertilizers (chlorides, sulphates), as well as with organic and mineral complexes (Table 4).

This situation lasts for a long period of time and is related to the buffer capacity of the soil absorbing complex, that is, the ability of the soil absorbing complex to prevent external chemical exposure to the ground. The buffering of the soil is associated with the granulometric composition and the content of organic matters.

In acidic soils, mineral fertilizers have an increasingly significant effect on soil reaction over time. The rate of acidification of limed soils depends on the dose of fertilizers, the pH level achieved by liming and soil buffering. The buffering of the soil depends on the content of organic and mineral colloids. The effect of small doses of lime on the soil pH under the conditions of water washing regime was short. In the third year, the soil reaction approached the initial level, five years later, under the influence of mineral fertilizers; the soil had a more acidic reaction than at the beginning of the experiment. Liming in half of the hydrolytic acidity influenced soil reaction for 5–6 years, and hydrolytic acidity in total for 10–12 years.

Large doses of lime supported the soil reaction for a longer period of time. In all cases, however, the prolonged use of high doses of mineral fertilizers significantly reduced the soil reaction and increased the washing of the bases. The change in the soil reaction when applying mineral fertilizers with acidic and limed soils can be described by the exponential function of the species $y = A \cdot e^{B \cdot x}$, where Y – reaction of the soil, A, B – coefficients; x – term (years), N1P1K1 – medium level of fertilizers; N2P2K2 – increased; N3P3K3 – high (Table 5).

**Table 4.** Influence of mineral fertilizers on the unlimed soil reaction

| In the presence of fertilizer | Year of observations | | | | | |
|---|---|---|---|---|---|---|
| | Before the experiment | 1 | 6 | 12 | 24 | 36 |
| Fertilizer free | 4.55 | 4.87 | 4.37 | 4.27 | 4.39 | 4.23 |
| Average | 4.55 | 4.83 | 4.21 | 4.21 | 4.15 | 4.02 |
| High | 4.55 | 4.67 | 4.00 | 4.00 | 3.79 | 3.68 |

**Table 5.** Models of changes in soil reaction over time

| In unlimed soil: | | | |
|---|---|---|---|
| 1. Fertilizer free | r = -0.26 | The significance level is not critical | |
| 2.N1P1K1 | r = -0.57 | P= 1 % | $Y=4.46 \cdot e^{-0.0058 \cdot x}$ |
| 3.N2P2K2 | r = -0.74 | | $Y=4.48 \cdot e^{-0.0105 \cdot x}$ |
| 4.N3P3K3 | r = 0.77 | | $Y=4.49 \cdot e^{-0.0133 \cdot x}$ |
| In soil limed with 1.0 Ng: | | | |
| 1. Fertilizer free | r = -0.80 | P= 1 % | $Y=1.898 \cdot e^{-0.0174 \cdot x}$ |
| | r = -0.92 | | $Y=6.768 \cdot e^{-0.0226 \cdot x}$ |
| 3.N2P2K2 | r = -0.95 | | $Y=6.883 \cdot e^{-0.0249 \cdot x}$ |
| 4.N3P3K3 | r = -0.95 | | $Y=6.975 \cdot e^{-0.0298 \cdot x}$ |

The results determining the metabolism forms of calcium in the experiment soil (Table 6) indicate significant losses of calcium in regions with high hydrothermal coefficient. In case of leaching (degradation) of bases and their removal together with the crop harvesting, the destruction of the soil absorbing complex, loss of soil fertility takes place. It is impossible to preserve soil fertility in the conditions of the north-western region without the creation of a soil-absorbing complex of large capacity due to the application of organic fertilizers and liming.

In the course of 36-year experiment, organic fertilizers were introduced only twice: under potatoes in 1985 (1st rotation) manure at a dose of 60t/ha and in 1991 (2nd rotation) – peat-manure compost at a dose of 20 t $ha^{-1}$. 36 years after the experiment began, a decrease in humus content in the soil was registered (Table 7).

The changes occurring in the soil under the influence of liming and long-term use of mineral fertilizers affect the nutrition pattern of plants and the migration capacity of substances in soils. There is a redistribution of substances in the soil horizons. This is confirmed by our long-term lysimetric studies. Under the influence of mineral fertilizers, liming process increases the reaction of the medium in the sub-arable horizons due to the migration of bases in them.

There is a decrease in hydrolytic acidity in these horizons. The content of mobile forms of phytotoxic elements in the soil of fertilized plots was higher than without mineral fertilizers, regardless of the lime dose. Liming reduces the number of fungi by 15–42 %. The number of bacteria consuming mineral forms of nitrogen increases by 2.3–4.7 times, the number of bacteria using organic forms of nitrogen – by 2.5–5.2 times, the number of oligotrophic bacteria – by 1.5–3.5 times, spore bacteria – by 1.1–2.1 times, actinomycetes – by 2.0 – 10.0 times.

**Table 6.** Change of calcium content in the experiment soil

| Dose of lime in Ng fractions | In the presence of fertilizer | Calcium content in soil, mg/kg | | |
|---|---|---|---|---|
| | | Liming in 1981 | 36 years after the lime introduction – 2016 | Repeated liming (½ dose) in 2017 |
| 0 | Fertilizer free | 430 | 159 | 221 |
| | Average | 430 | 87 | 216 |
| | High | 330 | 31 | 97 |
| 1.0 | Fertilizer free | 1050 | 459 | 632 |
| | Average | 980 | 503 | 656 |
| | High | 965 | 331 | 513 |
| 2.5 | Fertilizer free | 1100 | 525 | 619 |
| | Average | 1055 | 555 | 681 |
| | High | 1575 | 555 | 665 |
| *$LSD_{0.05}$ | | 205 | 62 | 67 |

*LSD – least significant difference

**Table 7.** Content of humus in the experiment soil in 2016 ( %). (humus content at the beginning of the experiment – 2.20 %)

| In the presence of fertilizer | Lime dose in Ng fractions (liming in 1981) | | | | | | Medium according to A (fertilizers) LSD $_{0.05}$ = 0.17 |
|---|---|---|---|---|---|---|---|
| | 0 | 0.25 | 0.5 | 1.0 | 2.0 | 2.5 | |
| Fertilizer free | 1.75 | 1.26 | 1.37 | 1.43 | 1.58 | 1.79 | 1.53 |
| Average | 1.89 | 1.90 | 1.62 | 1.73 | 1.40 | 1.57 | 1.68 |
| Increased | 1.62 | 1.75 | 1.84 | 1.63 | 1.76 | 1.64 | 1.71 |
| High | 1.73 | 1.66 | 1.76 | 1.84 | 1.88 | 1.96 | 1.80 |
| Medium according to B (lime), $LSD_{0.05}$=0.21 | | | | | | | |
| | 1.75 | 1.64 | 1.65 | 1.65 | 1.65 | 1.74 | |

$LSD_{0.05}$ for comparison of particular averages = 0.62

The application of moderate doses of mineral fertilizers during soil liming increases the number of bacterial microflora. Mineral fertilizers significantly reduce the number of bacteria without liming.

Long-term use of mineral fertilizers (120 kg and above) inhibits the development of bacterial microflora even in the presence of lime. Lime has a great influence on nitrification intensity and nitrate accumulation in soils with low humus content. This is due to the high acid sensitivity of nitrified bacteria. In our experiments, liming significantly increases the nitrification capacity of the soil (Table 8).

**Table 8** Potential nitrification capacity of the soil, N-NO3, mg/kg, 2017

| In the presence of fertilizer | Lime dose | | |
|---|---|---|---|
| | Without lime | By 1.0 Ng | By 2.5 Ng |
| Fertilizer free | 85.3 | 156.0 | 151.5 |
| Average | 76.7 | 201.3 | 257.0 |
| High | 62.5 | 294.2 | 329.4 |
| $LSD_{0.05}$ =68.4 | | | |

It was previously established that the negative effect of soil increased acidity on plants is due to the presence of mobile forms of phytotoxic elements in it. In the course of our experiment with the long-term application of mineral fertilizers, the content of lightweight forms of aluminum, manganese and iron in the soil was increased. This was observed both in acidic soils and in soils where lime was previously introduced. It is established that optimal conditions for the development of soil fungi are created with the content of lightweight manganese forms about 0.06 mg-eq per 100 g of soil and 4–6 mg of iron per 1 kg of soil.

The increased content of mobile forms of aluminum, manganese, and iron in the soil absorbing complex has a negative effect on plant development and bacterial microflora. Mobile aluminum most severely inhibits the development of microflora, consuming organic nitrogen sources and bacteria using mineral forms of nitrogen. Correlation and regression analysis showed that the relationship between the content of mobile aluminum and the value of nitrate accumulation is closer than of the pH value. This relationship is described by the parabola equation –

$$y = 16.71+1.50x6.26x^2$$

Both high and low levels of exchange manganese reduce nitrate accumulation in sandy soil with low humus content. The mobile manganese content in sandy soil in the amount of 0.025–0.035 mg per 100 g of soil is an optimal one for nitrification.

The nitrate content in soils with a reaction of 4.6–4.8 is usually low because high aluminum content inhibits nitrification. The nitrate content of steam plot soils is close in its value to the content in soils under vegetation only in the first phases of the crop development. In the future, it is higher than in soils under crops. This is due to the absorption of nitrates by crops.

The crop intake of nitrates was influenced by the content of exchange calcium in the soil. Without fertilization, this relationship was of average closeness (r=0.51). The value of calcium in nitrogen input to crops on fertilized plots increased (r=0.65). The use of nitrogen fertilizers at a dose of N120...135 kg of active ingredient significantly reduces the number of useful microflora in comparison with the use of moderate doses of fertilizers, which is one of the reasons for the decrease in nitrogen inputs to crops.

The liming process increases the coefficient of use of nitrogen fertilizers in barley by 2...3 times, oats – by 10...12 %, potatoes – by 7…11 %.When characterizing the potassium status of sod-podzolic soils, it is necessary to take into account the granulometric composition and mineralogical composition of soils, the level of liming and the soil provision with potassium, as well as the cations content of in the soil.

According to our data, potassium potential in limed soils can not serve as a criterion of crops provision with potassium. The antagonism or synergy of potassium and calcium cations depends on the biological characteristics of crops and the concentration ratio of elements in soil and soil solution. The proportion of light-moving and exchange potassium in SAC (soil adsorption complex) decreases in soils without the application of mineral fertilizers in case of liming.

In case of long-term introduction of high doses of mineral fertilizers, the share of metabolic forms of potassium in the arable horizon during the liming with 1,0Ng increases by 27 %, with 2.5 Ng liming – by 62 %; in the 20–40 cm horizon – by 55.8–77.5 %, respectively, and in the 40–60 cm horizon – by 7 and 165 %.The application of phosphorus fertilizers in sod-podzolic soils reduces the mobility of aluminum as a result of its binding by the orthophosphoric acid anion. Systematic application of phosphorus fertilizers leads to the increase in mobile phosphorus content in soils and to change of soil absorbing complex properties.

Buffer systems formed by metal salts with phosphoric acid play an important role in phosphorus-rich soils. This changes the relationship between the soil reaction and the content of mobile aluminum, manganese, iron, exchange bases, the hydrolytic acidity level. Liming of strongly acidic sod-podzolic soils increases the crops intake of phosphorus from soil and fertilizers. With the increase in the reaction level up to $pH_{KCl}$ 4.9–5.2 the coefficients of phosphorus intake from fertilizers increase by 3.0–6.8 times.

The reaction level optimal for crop growth in sod-podzolic soils with good phosphorus supply shifts towards lower pH values. For crops sensitive to acidity, calcium, which is part of phosphorus fertilizers, is essential. For field rotation crops the dependence of their yield on liming and mineral nutrition level is satisfactorily described by equations of the parabola:

- for barley –
$$y=23.65+0.34H+1.10N–0.175H^2–0.45N^2– –0.0056NH+0.019N^2H;$$
- for perennial grasses –
$$y=79.5+0.73H+0.76N–0.26H^2–0.72N2+0.076NH– –0.030N^2H;$$
- for winter rye –
$$y=25.23–0.096H+1.105N+0.0012H^2–0.475N^2+ +0.105NH+0.0216N^2H;$$
- for oats –
$$y=20.156+0.122H+0.853N–0.116N^2+0.035NH– –0.0062N^2H;$$
- for potatoes –
$$y=169.70–0.26H+12.08N+0.16H^2–1.82N^2+ +0.15NH+0.27N^2H,$$

where $y$ is the yield of crops, c $ha^{-1}$;

N, H – the doses of fertilizers and lime in conventional units.

Based on the materials obtained, in order to determine the ways to reduce the leaching of calcium and other substances from arable soils and to preserve fertility, the agrochemical concept of environmentally friendly mineral fertilizers was developed and experimentally proven [20].

## 4 Conclusion

Based on the results obtained in the course of a long-term field experiment on studying the effectiveness of the combination of lime and mineral fertilizer doses on sod-podzolic sandy soil enough information was obtained about the positive role of this method for the preservation of soil fertility. The data obtained are the key to control the evolution of soils during their agricultural use.

The lime has a great influence on nitrification intensity and nitrate accumulation in soils with low humus content, which is associated with high acid-sensitivity of nitrifying bacteria.

According to the obtained results, the potassium potential in limed soils can not serve as a criterion of crops provision with potassium.

Liming of strongly acidic sod-podzolic soils increases the intake of phosphorus from soil and fertilizers by crops. Calcium, which is part of phosphorus fertilizers, is essential for acid-sensitive crops.

The optimal reaction level for crop development is not constant. In case of a good supply of crops with nutrients, the optimal reaction level shifts to a more assiduous area.

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