Change in the soils' fertility level of tea agrocenoses in the transition to cultivation without mineral fertilizers in the humid-subtropical zone of Russia

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Abstract. Research was carried out on the basis of preserved field multifactor experiment on tea crop (*Camellia sinensis* (L.) Kuntze) in the conditions of the Sochi Black Sea coast. The application of NPK fertilizers in different doses and combinations according to the experimental scheme was carried out annually from 1986 to 2011. Since 2012, the use of fertilizers has been completely discontinued. The fertility indicators of long-fertilized brown forest acidic soils (in layers 0-20/20-40 cm) were compared with those after 7-8 years of fertilizer withdrawal. During the period of fertilizers' application, the level of soils' nitrogen supply significantly exceeded the control (by 30-75/30-56 mg/kg depending on the doses of nitrogen fertilizers). After the fertilizers' discontinuity, nitrogen supply level equalization occurred in all experimental options. The content of labile phosphorus in soils previously fertilized with high phosphorus doses (120 kg P_2O_5 ha^{-1} $year^{-1}$ and more), during the period of experiment's conservation decreased by 450-500/350-450 mg/kg, but exceeded the control in 2-2.5 times; in soils previously fertilized by low doses, the indicators have not changed significantly. In soils highly supplied with labile potassium, the content of the element decreased by 70-140 mg/kg. The yield of tea in 2019-2020 was equally low (12-26 cwt/ha) on all options, 2.2-3 times lower than fertilized plantations. After the fertilizers' withdrawal, there was a decrease in acidity (an average increase in pH by 0.18-0.24/0.12-0.20 units) of agrogenic-acidized soils and an increase in their oppressed respiratory activity (on average by 1.6 times). These changes reflect the tendency of soil self-restoration after the removal of the fertilizers' load.

1 Introduction

The Black Sea coast within Greater Sochi is characterized by a humid subtropical climate; it is the only region of industrial tea cultivation in Russia (small areas are present in Tuapse district of Krasnodar Krai and the Republic of Adygea). During the active development of the tea industry, the total area of land under tea plantations in the region

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reached 1,600 hectares (by the 1980s), the annual gross collection of raw materials was more than 7,000 tons, and production of ready-made tea – about 2,000 tons [1]. The task of achieving high yields was solved by the use of mineral fertilizers, primarily nitrogen – up to 350-500 kg N ha^{-1} $year^{-1}$, according to the adopted intensive technology used at that time [2].

For plucking tea crop, additional stimulation of growth processes is especially important, since young shoots (tea raw materials) are collected repeatedly during the growing season. This is achieved by the application of fertilizers with mineral nitrogen readily available to plants. At the same time, large soil nitrogen losses are compensated – its removal with 80-90 cwt/ha tea yield is 100-110 kg/ha [3]. Being the largest tea producer in the world (45% of world production, consumption and export [4]), China currently contributes 280-745 kg N of nitrogen per hectare every year (average annual rate – 553 kg N ha^{-1} $year^{-1}$), and a dose of 300-450 kg N ha^{-1} $year^{-1}$ is considered to meet the real need of tea plantations in nitrogen [5-8]. High-tech tea production in Japan is accompanied by the use of even higher doses of nitrogen fertilizers – up to 800 kg N ha^{-1} $year^{-1}$, while in Vietnam introduction amounts to 36-40 kg N ha^{-1} $year^{-1}$ [9].

Prolonged exploitation of soils in tea agrocenoses (perennial monoculture) leads to their significant changes, with acidification associated with the use of nitrogenous fertilizers being a generally acknowledged problem [8-13]. Long-term complex studies of plantations' productivity and fertility indicators' dynamics in conjunction with the agrogenic soil transformation processes development were carried out in the conditions of the humid subtropical zone of Russia under different schemes of mineral fertilizers' use [10, 11, 14-18]. The research results allowed to optimize the zonal tea fertilizing system on the basis of a trade-off between economic and environmental validity [3, 19]. The system implies a differentiated approach to the selection of doses based on the characteristics of a particular plantation (variety, age, yield, planned quality, soils supply, transformation degree). For high-yielding full-age plantations it was shown that regular nitrogen application at a dose of 200 kg ha^{-1} $year^{-1}$ (combined with 60 kg P_2O_5 and 50 kg K_2O ha^{-1} $year^{-1}$) makes it possible to obtain high quality raw materials, maintain high level of soil fertility without significant impact on the material and functional state of the soil [20]. The tea fertilizer system can be considered organo-mineral as large volumes of leaf fall and undercutting mass are annually introduced in the interrows, which contributes to the accumulation of humus [14]. The principles of biologization are met by the absence of mechanical tillage and pesticide treatment (with low pest damage in the region).

Unfortunately, in the conditions of many small tea-producing farms, the introduction of a scientifically justified system of mineral tea nutrition in the production practice is difficult. Extensive crop cultivation, non-systemic (random) use of fertilizers in random small doses has become predominant in recent decades. Individual tea-producing farms go on the way of promoting their tea as an organic product, for which they are forced to abandon the use of mineral fertilizers for many years. All this in the conditions of limited tea-appropriate lands calls into question the prospects of own tea production growth in Russia; threatens by the general degradation of agricultural systems of tea plantations.

In this regard, it is of theoretical and practical interest to assess the changes in soil fertility levels of tea plantations and their productivity generated by the long-term use of mineral fertilizers when switching to extensive cultivation in the conditions of the humid subtropical zone of Russia.

2 Materials and Methods

The research was carried out on the basis of long-term field multifactor experiment with fertilizers as part of the Geographical Network of Experiments of the Russian Federation (No. 023 in the register). The experiment was laid in 1986 on the young plantation of Kolkhida tea variety (1983 planting) on the territory of CJSC "Dagomyschay", Uch-Dere village, Greater Sochi. The soil of the experimental site is brown forest acidic (on the eluvial talus of argillites) [21] – the main tea-suitable soil of the region (Sochi Black Sea coast, moist subtropical zone).

The application of fertilizers according to the experimental scheme, as well as agrotechnical maintenance of the experimental plantation (clearing and trimming), harvesting and crop accounting were carried out annually during 1986-2011. The experimental scheme included 16 different combinations of NPK doses (in 4 gradations of doses – 0, 1, 2, 3), including a control option without fertilizers. The magnitude of the single nitrogen fertilizer dose grew as plants developed, but remained constant for phosphorus and potassium fertilizers. The doses used in the experiment and the total amount of mineral nutrition elements introduced into the soil during the entire period of fertilizer application are shown in Table 1. Experimental repetition was 2-fold, experimental plots size – 50 m^2, planting density – 0.3 m x 1.5 m (in rows and between rows). For a long period (over 25 years), model mini-plantations (experimental options) were formed within the experimental range with different levels of yield, soil fertility and degree of their agrogenic transformation.

Table 1. Doses and total quantities of nitrogen, phosphorus and potassium fertilizers introduced in long-term field experiment

Dose code	Nitrogen					Phosphorus		Potash	
	Doses by period, kg N ha^{-1} $year^{-1}$				Σ for 1986-2011, t N ha^{-1}	Doses, kg P_2O_5 ha^{-1} $year^{-1}$	Σ for 1986-2011, t P_2O_5 ha^{-1}	Doses, kg K_2O ha^{-1} $year^{-1}$	Σ for 1986-2011, t K_2O ha^{-1}
	1986-1988	1989-1992	1993-1999	2000-2011					
0	0	0	0	0	0	0	0	0	0
1	70	90	120	200	3,8	60	1,6	50	1,3
2	140	180	240	400	7,6	120	3,1	100	2,6
3	210	270	360	600	11,4	180	4,7	150	3,9

In 2012, the experience was preserved, the operation of the plantation (its agricultural maintenance and harvesting) was completely discontinued, including the application of fertilizers. Indicators monitoring of agrogenically transformed soils' condition in the absence of fertilizer load has been started. In 2017-2018, the plantation was re-commissioned (cleared, renovating trimming was carried out), but the application of fertilizers according to the experimental scheme was not resumed. This allowed to study the post-effect of fertilizers on soil fertility and agroecosystems' productivity in 2019-2020. Soil samples from the upper horizons (0-20 and 20-40 cm) were taken in order to assess soil condition and obtain a representative data sample on each of the options at 5-6 points.

When conducting laboratory tests, generally accepted methods [22] were used: pH_{KCl} (in salt extract 1 n. KCl) – potentiometrically (analyzer "Expert 001-3-0,1"); hydrolytic acidity – according to Kappen (in extract 1.0 n. CH_3COONa) titrimetrically; metabolic acidity and labile aluminum – according to Sokolov (in the extract 0,1 n. KCl) titrimetrically; metabolic calcium and magnesium – trilonometrically (1.0 n NaCl extraction); nitrate nitrogen (H_2O extraction) – disulfophenol method, colorimetrically (spectrophotometer USF-01); ammonia nitrogen (2% KCl extraction) – colorimetrically with Nessler reagent; easy hydrolysable nitrogen – according to Turin and Kononova (extraction 0.5 n H_2SO_4) colorimetrically with Nessler's reagent; labile phosphorus and potassium – according to Oniani(extraction 0.1 N H_2SO_4) colorimetrically and emission-spectrometrically (atomic absorption spectrometer “KVANT AFA-A”).

The generalization of the experimental material was carried out using descriptive statistics in the Microsoft Excel program (at P = 0.95). The diagrams represent mean ± standard deviation. A code was used to indicate options or groups of options – the number of single doses of relevant elements (NPK) during the fertilization period according to the scheme.

3 Results and Discussion

The change in fertility level and soil condition of model experimental mini tea plantations 7-8 years after its preservation was evaluated according to the main indicators (content of NPK labile forms, acid-base properties) in comparison with the final period of fertilizer application (2010-2012).

In the final phase of active operation, the soils of mini-plantations long fertilized with single, double or triple doses of nitrogen, reached supply levels of easy hydrolysable nitrogen [15], on average exceeding control (000) by 1.5-2 times – by 30/30, 63/48 and 75/56 mg/kg respectively (in layers 0-20/20-40 cm) (Figure 1). After the fertilizers' withdrawal, already in the first years [23] a decrease in the easy hydrolysable nitrogen content to a level close to the control level (Figure 2) was observed. Data from 2019-2020 demonstrated a complete absence of differences between options on the content of mineral nitrogen forms (Figure 1). Rapid fall in the soils supply level with nitrogen is quite predictable, since it is known that the stock of labile compounds of this element is formed only for a short time, and the bulk of the soil nitrogen is enclosed in complex slowly mineralizing organic compounds, immobilized in humus.

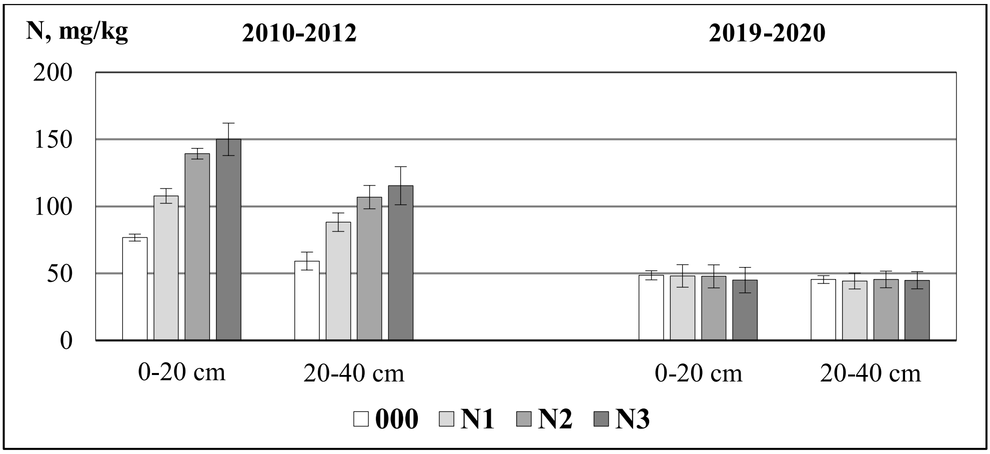

Fig. 1. Soil supply with nitrogen at the final stage of fertilizer application (2010-2012 – easy hydrolysable nitrogen) and after experiment's preservation (2019-2020 – mineral forms), average in groups of options with 1-2-3 N doses.

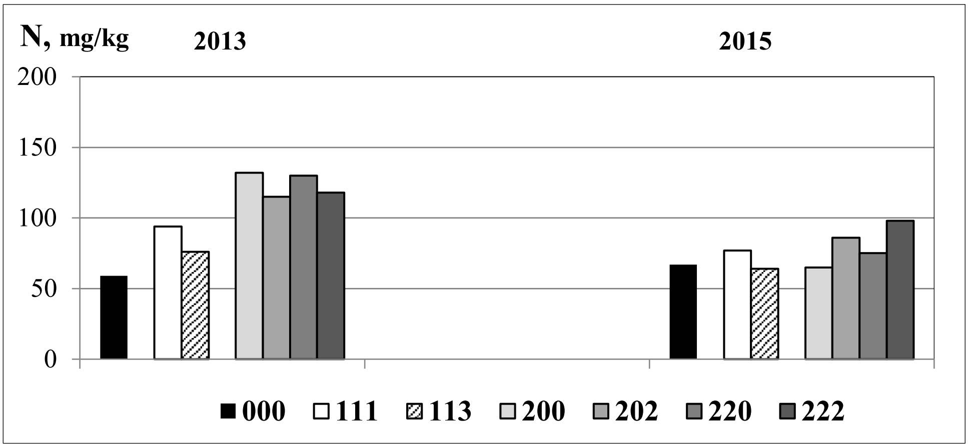

Fig. 2. Change in the content of easy hydrolysable nitrogen in soil (0-20 cm) of model experimental mini-plantations in the first years after fertilizer's withdrawal.

Prolonged use of phosphate fertilizers led to a significant increase in the labile phosphates reserves in the experimental plots' soil [16]: 3-4-fold against the background of double and triple doses – on average by 840-930/ 440-600 mg/kg (in layers 0-20/20-40 cm); 1.5-fold on the background of single doses – 230/60 mg/kg (Figure 3, 2010-2012). Labile phosphorus is characterized by high spatial variability of indicators (30-40% or more), associated with uneven application of phosphate fertilizers and low phosphates mobility in acidic soils. In this regard, in the first few years of experiment's conservation there was no tendency to decrease its quantity in the root layer [23]. As a result of the 2019-2020 soil survey, it was found that on options not previously fertilized with phosphorus, as well as fertilized with single P doses, the level of labile phosphorus soil availability has not changed significantly during the preservation period. On options previously fertilized by double or triple doses of phosphorus fertilizers, a 1.5-1.8-fold decrease in the labile phosphorus content relative to the level of 2010-2012 was revealed after 7 to 8 years of absence – on average by 450-500/350-450 mg/kg in layers 0-20/20-40 cm (Figure 3). However, the phosphorus content here still exceeded the control by 2-2.5 times.

Change of the soils' phosphate regime, structure of their phosphate fund (ratios of different groups of phosphate compounds, fractions of mineral phosphates) after removing the fertilizers' load requires further research. The studied brown forest acidic soils (clay, rich in sesquialteral oxides) have a high ability to absorb and fix incoming phosphorus. This suggests long-term preservation of the total phosphorus reserve created using phosphorus fertilizers, despite the revealed decrease in labile phosphate content. Earlier fractional composition study of mineral phosphates in soils against the background of the phosphorus fertilizers application showed that the growth of gross phosphorus content was accompanied by an increase in the labile phosphates proportion; the share of labile phosphates (according to Oniani) from the sum of the most labile fractions (Rs-P+Al-P on Chang-Jackson) was also growing [24].

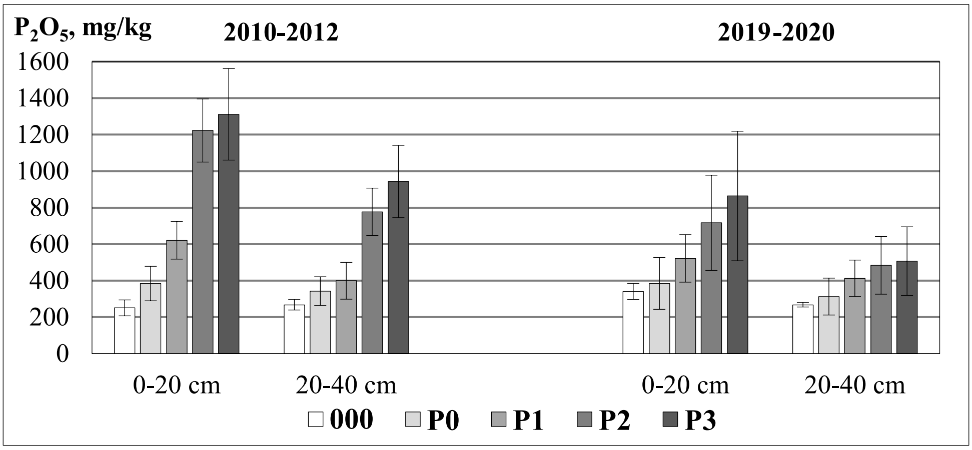

Fig. 3. Provision of soils with labile phosphorus at the final stage of fertilizer application (2010-2012) and after experiment's preservation (2019-2020), average in groups of options with 0-1-2-3 doses of P.

The supply level of brown forest acidic soils with potassium formed during the fertilizer's introduction period depended on the combination of applied potassium and nitrogen doses determining the yield of plantations, elements' withdrawal, as well as soil acidification and potassium lability [17]. At the same time, due to the dynamic equilibrium between various forms of potassium [25], a relatively constant level of labile element's forms peculiar to this soil was maintained. A slight decrease in labile potassium content (on average by 40-60 mg/kg relative to control group N0K0) was found on nitrogen-intensive but no potassium fertilizers (N2K0) or with a low potassium dose (N3K1) (Figure 4, 2010-2012). When applying potash fertilizers in equal amounts of single doses with nitrogen (N1K1, N2K2, N3K3) or exceeding (N1K3), the content of labile potassium in the layer of 0-20 cm was above the control by 60-100 mg/kg. The study of the potassium forms complex showed that the increase in the labile potassium content reflects its accumulation in exchange form but can also be provided by the exchange compounds flow against the background of increasing acidity. The decrease in the labile potassium level to 300 mg/kg and below reflect significant changes in potash status of these soils: depletion of potassium reserve and consumption of its exchange and non-exchange forms by 25-50% [17].

During the experiment's preservation period on options with previously low level of labile potassium (N2K0 and N3K1), no significant changes were revealed. On the options that previously had an increased element's content there was a reliable decrease by 1.3-1.4 times (by 70-140 mg/kg) relative to the level of 2010-2012 (and by 50-95 mg/kg relative to control) (Figure 4). To understand the true extent of potassium reserves' soil depletion, it is necessary to assess changes in the entire element forms' complex.

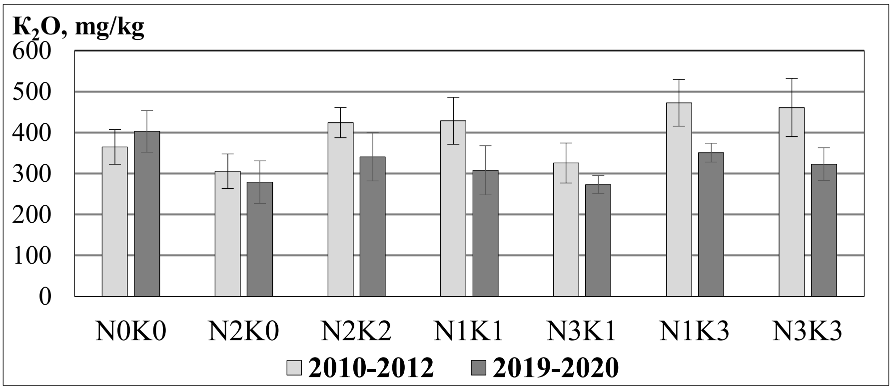

Fig. 4. Soils provision with labile potassium (0-20 cm layer) at the final stage of fertilizers' application (2010-2012) and after experiment's preservation (2019-2020), average by groups of options of N and K doses combinations.

The soil condition assessment according to the acid-base properties' complex after 7-8 years of experiment's conservation showed a reduction in previously achieved differences in terms of agrogenic acidification. The results are presented on the example of the integral indicator pH_{KCl} (Figure 5). After prolonged nitrogen fertilizers use (the main acidification factor) in single, double or triple doses, pH_{KCl} values were reliably lower by 0.44-0.82/0.25-0.55 units (in layers 0-20/20-40 cm) in relation to control-000 with no changes in acidity [11]. In the absence of direct fertilizers' influence, the pH $_{KCl}$ indicators rose to 2019-2020, both in the layer 0-20 and 20-40 cm – on average by 0.18-0.24 and 0.12-0.20 units, respectively. A significant decrease in the soils' acidification degree of tea plantations indicates a self-restoration tendency of agrogenically-modified soils after removing the fertilizers' load. The normalization trend of intensely fertilized soils' oppressed functional state after fertilizer withdrawal in increasing their respiratory activity was revealed, which went up from 45 to 73 mg CO_2/kg on average per season, but so far was lower than the control (80-90 mg CO_2/kg) [26].

Chinese researchers studied the organic fertilizer's application as an alternative to mineral fertilizers and a way to weaken the acidity of soils. The results showed low efficiency of this agrimethod: the introduction of 6 t/ha of manure per year slightly increased the pH of the topsoil, but further acidification of deeper layers occured because of downward movement of organic acids [27].

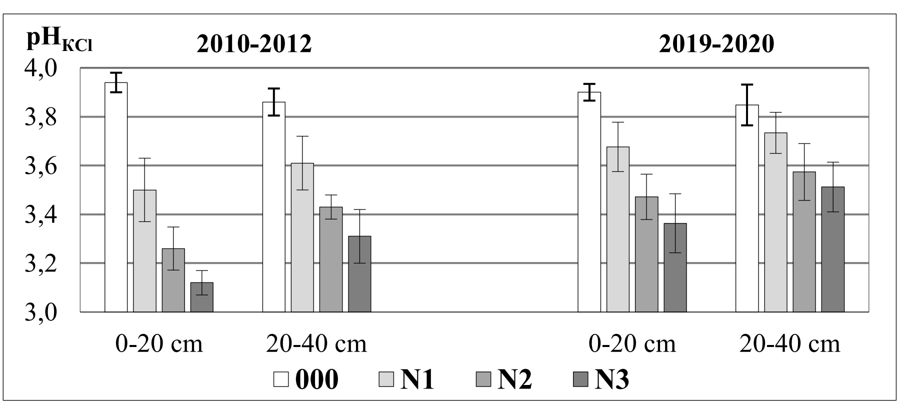

Fig. 5. The soils' acidity with different degrees of agrogenic acidification associated with the nitrogen fertilizers' load before and after experiment's preservation (average in groups of options with 1-2-3 N doses).

The yield of model mini tea plantations 7-8 years after the termination of fertilizer application in the conditions of 2019 and 2020 (atypical humid-cool and prolonged dry summers, respectively) was equally low regardless of the previously used fertilizers' doses – on average 26 and 12 cwt/ha, respectively (Figure 6). Prior to the experiment's preservation, such yield in similar weather conditions was in options without the use of nitrogen fertilizers [19]. The yield of the same plantation within the existing experiment in 2019-2020, with microelements against the background of N240P70K90, was higher by 2.2-3 times (Figure 6). With optimal mineral nutrition and favorable weather conditions, the yield of tea plantations (Kolkhida variety) can reach 100-120 cwt/ha.

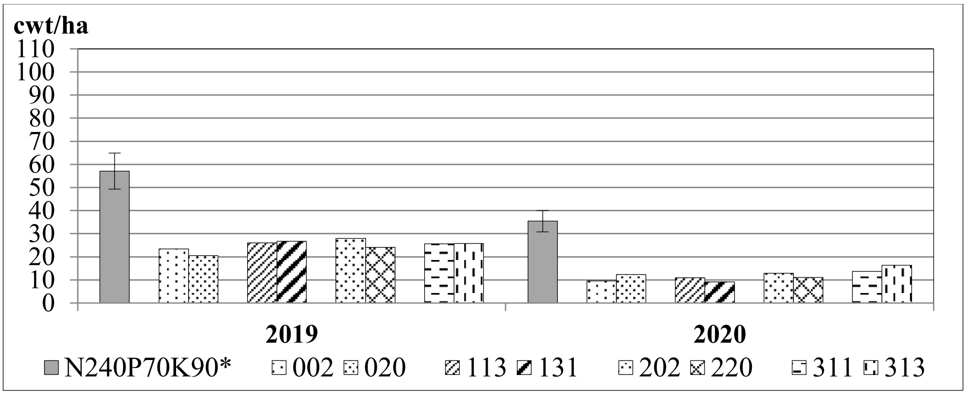

Fig. 6. Yield of model mini tea plantations of preserved experiment in 2019-2020 in comparison with average yield against the background of N240P70K90 (*– average in experiment with microelements).

4 Conclusions

The study results on the basis of preserved (in 2012-2020 period) multifactor field experiment with fertilizers on tea culture in humid subtropical zone conditions of the Russian Federation convincingly showed that after the removal of mineral fertilizers there was a significant drop in the previously achieved fertility level of brown forest acidic soils and crop yields.

The level of soils supply with nitrogen elevated by 1.5-2 times relative to control created as a result of prolonged nitrogen fertilizers' use significantly decreased after 3 years after their introduction stopped. 7-8 years after the experiment's preservation, there were no reliable differences between options in the content of mineral nitrogen forms.

In options where previously phosphorus fertilizers were introduced in double or triple doses (120-180 kg P_2O_5 ha^{-1} $year^{-1}$), soils had a 3-4-fold increase in phosphorus supply to the beginning of the experiment's preservation. As a result of fertilizer withdrawal, the content of labile phosphorus decreased by 1.5-1.8 times from the previous level, but exceeded control by 2-2.5 times. In options using low doses of phosphorus and on the control, there were no significant changes in the indicator during the preservation period.

In soils of model plantations that reached high potassium supply after prolonged application of potassium fertilizers, the content of movable potassium during the experiment's preservation period has significantly decreased both relative to the previous level (1.3-1.4 times) and relative to control. Soils that at the experiment's conservation beginning had reduced element content against the background of intensive nitrogen nutrition in the absence or lack of potassium did not have significant changes further.

With extensive cultivation type without the use of mineral fertilizers (especially nitrogen), the potentially possible productivity of tea plantations was not realized. In 2019 and 2020, the average experimental yield was 26 and 12 cwt/ha, which was 2.2-3 times lower than in the plantation plot where N240P70K90 was introduced. Regardless of the previously used fertilizers" doses and the level of soil fertility, the differences between the options were leveled during the period of experiment's conservation.

Along with the negative effects of cultivation without mineral fertilizers for tea plantations' agrocenoses, a positive trend of soil condition changes from an ecological point of view was revealed. Decreased acidity of agrogenically acidified soils (an average increase of pH by 0.2 units), as well as increased respiration activity (on average by 1.6 times) showed a pronounced tendency of soils' self-restoring, remission of their functional state after removing the fertilizers' load.

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