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Soils of external islands of the Gulf of Finland: Soil pollution status and dynamics in abandoned agricultural ecosystems

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Abstract: External islands of the Gulf of Finland are an archipelago of relatively small islands located in central-eastern parts of the gulf. These islands are unique natural environments that represent an informative model for the evaluation of former agricultural soil dynamics in abandoned agricultural landscapes. Soils of these islands have been in a fallow state for about 70 years, although before that, they were arable vegetable soils of Finnish settlements for a long time. The morphological pedodiversity of external islands of the Gulf of Finland was studied during a complex expedition that took place within the framework of the program "My Region" in 2019 and was supported by Nord Stream 2 AG. The determination of main soil characteristics was carried out using standard analysis procedures. The unique soils of these areas could be used for the evaluation of the long-term evolution of anthropogenically developed soils after being in an abandoned (fallow) state. Data on soil morphology, taxonomy state and agrochemical soil characteristics are discussed, as are current soil pollution processes of these remote areas based on trace elements. Lands of external islands of the Gulf of Finland are characterised by a wide diversity of soil patterns at different stages of development.

Keywords: abandoned agricultural landscape; agrochemical characteristic; fallow soils; Seskar, Moshchny, Maly, Bolshoi Tyuters islands; soil contamination

The Leningrad region is one of the Russian regions with the most ancient history of agriculture. Highly old cultivated soils – plaggen soil – are found around ancient settlements, which indicates intensive agricultural use in the past (Blume & Leinweber 2004; Giani et al. 2004). Soils with a thick humus horizon were formed as a result of the prolonged application of organo-mineral fertilizers. There are many abandoned lands in the region, which can serve as a model for studying the degradation and amelioration of soil and ecosystems over time.

The external islands of the Gulf of Finland are an archipelago of small islands located in the central-eastern part of the gulf. Islands include Gogland, Roadsher, Bolshoi and Maly Tyuters, Moshchny, Nerva, Maly, Seskar, Sommers, Virgin Islands, and smaller nearby islands. These islands have a rich history. The Finnshave traditionally carried out fishing

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and agricultural land development there since about 1104. They applied an adaptive land-use management strategy in those days, which became a transformative strategy over time, consisting of an "alteration" of the natural environment for the convenience of using mechanised technologies. Therefore, abandoned fallow lands on the external islands of the Gulf of Finland (old plaggen soils) are of particular interest. The most studied are the soils of Gogland and Bolshoi Tyuters. Soils of the Gulf of Finland islands and in the Leningrad Region in a whole were shortly described by Pestryakov (1973), Gagarina et al. (2011), Shamilishvily et al. (2018). Nevertheless, various lithological, geomorphological, etc conditions of the Gulf of Finland islands require research in terms of their relationship with the soil-forming process and edaphic conditions for biodiversity formation in island territories.

The study of abandoned land properties of the Gulf of Finland external islands makes it possible to investigate the regularities of the changes that occur in these soils over time. Knowledge of ongoing processes direction will help to reveal the ultimate solution regarding the issue of certain lands reintroduction into agricultural circulation or reasons for avoiding their use, as well as recommendations development for fallow lands use for other purposes (for example, hay harvestings, pasture, or forestry needs). Therefore, the main goal of the study is to show detailed information about the main elements of soil cover and to assess the current environmental soil state and agrochemical soil fertility to trace the long-term evolution of anthropogenically developed soils after 70 years of abandonment.

MATERIAL AND METHODS

Study area. Abandoned fallow soils of the external islands of the Gulf of Finland were examined to study the environmental state and post-agrogenic transformation of fallow soils on Seskar, Moshchny, Maly, Bolshoi Tyuters islands (Figure 1).

The climate of this region can be characterised as transitional from continental to maritime with moderately warm summers, rather long moderately cold winters, and unstable weather conditions. Basic climatic parameters are annual temperature (3.7–5.2 °C), average February temperature (–6.2 to –8.5 °C), average July temperature (16.9–17.6 °C), and annual precipitation (500 to 650 mm).

The geology of the eastern part of the Gulf of Finland area is characterised by high variability due to the geological development of the region since the degradation of the last glaciation (Filippov 2009; Ryabchuk et al. 2017; Terekhov & Yurmanov 2019). Quaternary deposits form an almost continuous cover on a surface of the pre-quaternary substrate and are widely developed within the eastern part of the gulf (Malakhovsky & Markov1969). A complex of Late Valdai glacial formations of the Upper Neopleistocene lies at the base of the geologic cross-section; the earlier moraine and intermorainal horizons were eroded during the last glaciation and were preserved only locally in paleovalleys (Kvasov 1975; Spiridonov 1989).

Islands belong to the North-Primorsky landscape region and a group of low-lying glacial and lacustrine sandy and sandy loam plains. Most islands are granite monoliths washed by the Gulf of Finland. The

Figure 1. Study sites: external islands of the Gulf of Finland (Ria News, Sputnik)

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relief of large islands is characterised by selga-type landscapes (low ridges) and inter-ridge depressions. Selga-type landscapes are characterised by outcrops of crystalline rocks (mainly rapakivi granites). Easkers slopes are covered with a thin layer of sandy and stony moraine. Organo-lithogenic soils (Lithic Leptosols – hereinafter soil names in brackets are according to WRB) with a thickness of up to 3–5 cm are formed on top of easkers. Peaty-podzolic humic-ferrugenous-illuvial soils (Histic Albeluvisols) develop in places with significant moisture, while layered marshy gley soils (Tidalic Fluvisols) appear in coastal areas. Soddy pseudogley (Gleyic Albeluvisols) and gley soils (Gleysols) have developed on clay and sandy sediments in the vicinity of former villages under meadow vegetation (*Poa pratensis*, *Agrostis alba*, *Festuca pratensis*, etc.).

Analytical methods. Soil-environmental studies were carried out using standard methods for describing soils (18 soil pits: 11 – Moshchny Island, 4 – Seskar, 2 – Maly, 1 – Bolshoi Tyuters), as well as the morphological description and laboratory analyses aimed at studying chemical, physical, and biological soils properties. More than 70 soil samples were analysed.

The determination of main soil characteristics was carried out using standard analysis procedures (US EPA 1993; Rastvorova et al. 1995; Kuo 1996; Vorobyova 2006; GOST 26489-85; GOST 54650-2011).

Soil diagnostics were carried out according to the "Classification and diagnostics of soils of Russia" (Shishov et al. 2004) and the World Reference Base for Soil Resources, (IUSS Working Group WRB 2015). For both classification systems correlation table with abbreviations is presented (Table 1). The content of heavy metals in individual extracts was determined by the AAS method using flame detection. In order to characterise the environmental soil state a quantitative index of soil pollution by heavy metals (geo-accumulation index (Igeo) (Muller 1979) and total soil pollution index (Zc) were calculated.

The data's normal distribution was verified, and an analysis of variance (ANOVA) and post hoc test were performed.

RESULTS AND DISCUSSION

Soil cover and soil characteristics. The soil cover of studied islands is characterised by a predominance of shallow soils – Lithozems, Petrozems, Psammozems, and Arenosols (Shishov et al. 2004). They are characteristic for rocky outcrops, colluvium, and rubble eluvium of granite rocks. Moreover, Gray-humus soils (AR) with a more developed profile are often found. Podzols and Podburs (Podzols) are quite typical for inter-selga-type landscapes at altitudes of 60–70 m a.s.l. There are few anthropogenically transformed soils (Agrozems and Agro-gray-humus soils) (PA) on islands. pH_{H2O} varies from a strongly acidic reaction to a neutral one, increasing towards the lower horizon (the difference was statistically significant ($P < 0.05$)) (Table 2). Table 2 shows the hydrolytic and exchangeable acidity, as well as the results of basal respiration.

Table 1. Correlation table for soil types in case of classification systems (Russian and WRB)

No.	Russian classification	WRB 2015	Abbreviations
1	Gray-humus sandy loam soil	Arenosol	AR
2	Agro-gray-humus sandy loam soil	Plaggic Anthrosol	PA
3	Podbur	Entic Stagnic Podzol	ESP
4	Illuvial-ferrugenous Podzol formed on sorted fluvio-glacial sandy loam sediments	Albic Fluvic Podzol	AFP
5	Agrozem	Anthrosol	Ant
6	Eluvozem formed on a granite rock	Albic Podzol	AP
7	Illuvial-ferrugenous-humus podzol	Albic Humic Podzol	AHP
8	Psammozem gray-humus formed on sea sandy loam sediments	Tidalic Arenosol	TA
9	Gray-humus sandy loam soil formed on eolian sands	Arenosols	AES
10	Polygenetic Podzol formed on eolian sandy loam sediments underlain by sea sands	Podzol over Tidalic Umbrisol	PTU
11	Ferrugenous illuvial podzol on sorted fluvioglacial sandy loam sediment	Rustic Podzol	RP

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Table 2. Chemical and biological soils properties of studied islands

No. of soil pit	Horizon	pH_{H_2O}	pH_{KCl}	Hydrolytic soil acidity (mmol/100 g)	Exchange soil acidity (mmol/100 g)	Soil basal respiration (mg CO_2/100 g/day)
AR						
F1	AY	6.4	5.5	0.37	0.10	0.04
F1	1C	6.0	5.4	0.72	–0.10	0.03
F1	2C	6.5	5.0	0.26	0.10	0.03
F1	3C	6.4	5.4	0.32	0.30	0.02
PA						
F2	AY	5.5	4.4	2.07	0.50	0.02
F2	AC	6.3	4.9	0.55	–0.10	0.03
F2	2C	6.1	5.4	0.80	0.20	0.02
ESP						
F3	OT	4.3	3.2	–	0.40	0.04
F3	BF	5.2	3.7	4.92	1.00	0.01
AFP						
F4	O	4.5	3.5	50.30	0.20	0.04
F4	E	4.9	3.6	3.19	1.70	0.04
F4	BF	6.0	4.7	0.95	0.90	0.02
F4	C	6.2	4.7	0.70	0.50	0.02
Ant						
F5	0–10	5.4	4.7	4.23	0.10	0.04
F5	10–20	5.6	5.0	3.79	0.80	0.05
F5	20–40	6.4	5.1	1.26	0.40	0.04
F5	C	6.4	5.1	1.60	0.00	0.05
AP						
F6	O	4.9	3.7	88.20	0.30	0.04
F6	E	5.3	4.0	2.25	0.70	0.04
AHP						
F7	O	4.4	3.4	1.28	0.60	0.04
F7	E	5.5	4.1	2.07	0.20	0.05
F7	B	5.8	4.2	1.23	1.00	0.02
F7	C	6.3	5.5	0.30	–0.10	0.04
TA						
F8	W	6.5	5.5	0.24	0.00	0.04
F8	C	6.7	5.2	< 0.23	–0.10	0.02
AES						
F9	AY	5.7	4.4	0.87	0.40	0.03
F9	C	6.4	5.3	0.28	–0.10	0.03
PTU						
F10	O	4.5	3.3	84.40	1.00	0.04
F10	E	5.2	4.3	1.37	0.50	0.07
F10	B	5.7	4.2	0.91	0.50	0.06
F10	BF	6.3	5.0	0.81	0.00	0.07
F10	[O]	5.0	3.8	4.42	2.60	0.04

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Table 2 to be continued

No. of soil pit	Horizon	pH_{H2O}	pH_{KCl}	Hydrolytic soil acidity	Exchange soil acidity	Soil basal respiration ($mg CO_2/100 g/day$)
				(mmol/100 g)		
RP						
F11	1	5.8	4.8	0.63	0.10	0.06
F11	2	5.3	4.7	2.99	0.20	0.06
F11	3	5.8	4.4	1.50	2.30	0.02
F11	4	5.5	4.7	0.85	0.10	0.03
F11	5	5.6	4.6	0.68	0.10	0.05
F11	6	5.8	4.6	1.28	1.40	0.05
F11	7	6.3	4.9	0.66	–0.10	0.05
Post hoc test		$P << 0.05$	0.46	$P << 0.05$	0.07	0.34
Significance		sign	insign	sign	insign	insign

For the soil types abbreviation see Table 1

The carbon content in topsoil showed relatively high variability (0.05–27.6%). This was due to the type of topsoil (O (litter)/OT (peaty forest litter) or AY (gray-humus horizon)), different rates of former anthropogenic fertilization of the soil, and the time since the land was last used (they are practically abandoned territories today). Topsoil horizons of studied soils (AY/O/OT) have a maximum C content (Figure 2) throughout the whole soil profile (16.11% C content on average for O/OT and 1.44% in AY). Down the soil profile, there is decreasing in organic matter (SOM) content with regard to mineral horizons. Comparative analysis of SOM elemental composition using atomic ratio diagrams (Figure 3) made it possible to distinguish a group of Moshchny Island soils, where organic matter has a significantly higher aliphatic content. Alfehumus soils also form a separate group of SOM characterised by an increase in the proportion of aliphatic chains (in terms of H : C ratio).

Heavy-metal soil contamination. The trace element status of soils investigated in terms of heavy metals is shown in Table 3. The total index of soil pollution (Zc) by heavy metals was calculated over the entire soil profile, which makes it possible to assess the migration of these elements down the profile. The total pollution indicator in upper horizons is characterised by low values (Zc < 16), which means they are within the permissible (tolerable) level of contamination.

The calculation of the geo-accumulation index (Igeo) and its environmental interpretation (Dauwalter 2012) showed that soils are moderately/heavily polluted by only one element: Pb (in the case of Agrozem at Seskar Island). There were weak levels

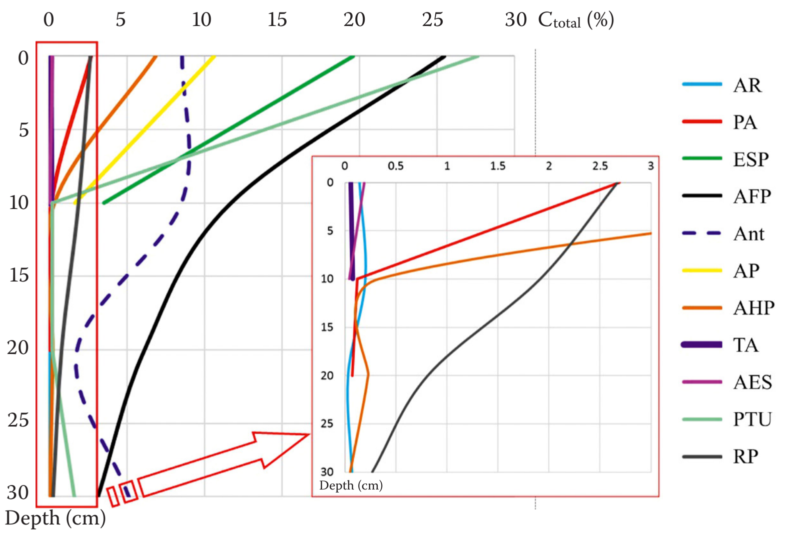

Figure 2. C content in fallow soils on studied islands (soil names abbreviations are given in accordance with Table 1)

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Table 3. Trace elements status of studied soils (heavy metals content in mg/kg, Igeo in parenthesis)

No. of soil pit	Horizon	Cu	Pb	Zn	Cd	Ni	Cr	Zc	Trace elements status
AR									
F1	AY	0.64 (–5.40)	0.27 (–6.72)	8.10 (–3.00)	0.03 (–3.02)	0.48 (–5.59)	0.50 (–5.22)	–3.50	allowable
F1	1C	0.62 (–5.44)	0.49 (–5.86)	7.81 (–3.05)	0.05 (–2.24)	0.56 (–5.37)	0.86 (–4.44)	–3.40	allowable
PA									
F2	AY	1.67 (–4.02)	4.38 (–2.71)	19.60 (–1.72)	0.07 (–1.83)	0.96 (–4.58)	0.84 (–4.47)	–2.70	allowable
F2	AC	0.69 (–5.29)	0.45 (–5.98)	9.17 (–2.82)	0.04 (–2.54)	0.54 (–5.40)	0.75 (–4.65)	–3.40	allowable
ESP									
F3	OT	5.38 (–2.33)	39.10 (0.45)	25.90 (–1.32)	0.47 (0.89)	3.90 (–2.56)	3.00 (–2.64)	2.00	allowable
F3	BF	0.65 (–5.38)	2.94 (–3.29)	6.93 (–3.22)	0.06 (–2.09)	0.60 (–5.26)	0.90 (–4.38)	–3.30	allowable
AFP									
F4	O	0.97 (–4.80)	10.50 (–1.45)	11.00 (–2.56)	0.11 (–1.17)	0.96 (–4.58)	0.95 (–4.31)	–2.40	allowable
F4	E	0.27 (–6.64)	2.03 (–3.82)	3.74 (–4.11)	0.05 (–2.44)	0.25 (–6.51)	0.01 (–11.39)	–3.50	allowable
Ant									
F5	0–10	15.65 (–0.79)	207.30 (2.85)	86.00 (0.41)	0.17 (–0.57)	1.89 (–3.60)	9.47 (–0.99)	10.80	allowable
F5	10–20	39.22 (0.54)	147.50 (2.36)	81.40 (0.33)	0.17 (–0.58)	1.44 (–4.00)	7.37 (–1.35)	8.90	allowable
AP									
F6	O	0.89 (–4.92)	3.06 (–3.23)	6.75 (–3.26)	0.13 (–0.94)	0.80 (–4.84)	0.92 (–4.35)	–2.80	allowable
F6	E	0.65 (–5.38)	3.21 (–3.16)	5.04 (–3.68)	0.06 (–2.13)	0.83 (–4.79)	1.16 (–4.01)	–3.30	allowable
AHP									
F7	O	0.52 (–5.70)	3.38 (–3.08)	5.65 (–3.52)	0.14 (–0.91)	0.66 (–5.12)	0.67 (–4.81)	–2.80	allowable
F7	E	0.13 (–7.70)	0.98 (–4.87)	2.91 (–4.47)	0.13 (–0.98)	0.34 (–6.06)	0.48 (–5.28)	–3.10	allowable
TA									
F8	W	0.19 (–7.15)	1.03 (–4.80)	3.16 (–4.35)	0.07 (–1.94)	0.40 (–5.84)	0.74 (–4.66)	–3.40	allowable
F8	C	0.20 (–7.08)	0.33 (–6.43)	3.88 (–4.06)	0.13 (–0.97)	0.33 (–6.12)	0.77 (–4.61)	–3.10	allowable
AES									
F9	AY	0.40 (–6.08)	2.02 (–3.83)	6.32 (–3.35)	0.05 (–2.46)	0.66 (–5.13)	0.71 (–4.73)	–3.40	allowable
F9	C	0.32 (–6.40)	0.79 (–5.17)	5.85 (–3.47)	0.14 (–0.87)	0.40 (–5.84)	0.88 (–4.41)	–3.00	allowable
PTU									
F10	O	1.62 (–4.06)	7.65 (–1.91)	21.60 (–1.58)	0.22 (–0.21)	1.50 (–3.94)	2.14 (–3.13)	–1.60	allowable
F10	E	0.00 (–13.14)	0.40 (–6.15)	2.21 (–4.87)	0.11 (–1.21)	0.16 (–7.16)	0.24 (–6.28)	–3.30	allowable
Post hoc test		$P << 0.05$	$P << 0.05$	$P << 0.05$	0.15	$P << 0.05$	$P << 0.05$	$P << 0.05$	
Significance		sign	sign	sign	insign	sign	sign	sign	

Igeo – geo-accumulation index; Zc– total soil pollution index; for the soil types abbreviation see Table 1

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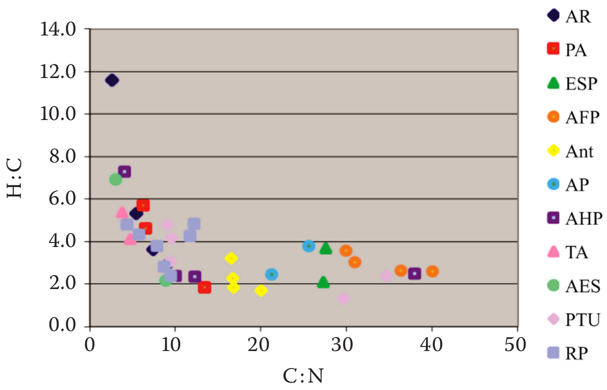

Figure 3. Soil organic matter Van Krevelen diagram of fallow soils on studied islands

For the soil types abbreviation see Table 1

of technogenic pollution by Cu, Zn, Cd, Ni, and Cr for all studied soils (Table 3). Therefore, Pb should be considered as a priority pollutant in these soils. The difference between heavy metal contents was statistically significant for all elements (P <0.05).

The actual concentrations of heavy metals' mobile forms in soils were compared with their control content in arable layer of natural Soddy-podzolic soil from the northwest Russia (Matinyan et al. 2007). For example, the actual content of Cu mobile forms in all samples is below the control value (2.7–5.5 mg/kg). Agrozem (Ant) on Seskar is the exception with about 3.53 mg/kg. The average Zn content exceeds the control level (1.2 mg/kg) by more than 10 times and reaches 16.15 mg/kg. Nevertheless, the soil is assessed as uncontaminated. Based on the results of the study, it can be concluded that soil contamination of surveyed areas is not a priority with mobile forms of Cu and Zn. A high anthropogenic impact on soils of external islands is noted, while Zn and Cu pollution is non-specific and does not always manifest.

Nutrient content. Data on nutrient content in soils are presented in Figure 4. Balance disruption of P deposits in fallow soils can significantly slow down the soil fertility restoration due to the fact that there are no natural sources of replenishment of P deposits. According to the results obtained, the maximum P content occurs in the upper horizons of studied soil profiles (59–304 mg/kg) (PA and RP at Moshchny and Bolshoi Tyuters). The P_2O_5 content decreases from 28 to 241 mg/kg in the middle and lower horizons.

K_2O accumulates mainly in the upper horizons of studied soils (from 5 to 642 mg/kg). Soils contain less P and K in comparison with fallow non-island soils of St. Petersburg and the Leningrad region. The content of NH_4^+-N ranges from 11.49 to 138.30 mg per kg in the upper horizons of studied soils and from 10.21 to 37.53 mg/kg in lower horizons. This reveals a more or less clear trend of the vertical distribution of NH_4^+-N.

The N-NO_3^- content characterises a supply of mineral nitrogen to the soil. The values of this parameter are significantly lower than that of NH_4^+-N and vary widely from 0.42 to 6.98 mg/kg. The low concentration can be explained by high element mobility and its migration with sediments. In contrast to P and K, NH_4^+-N and N-NO_3^- is contained in soils of studied islands in greater quantities than in abandoned fallow soils of St. Petersburg and the Leningrad region. The difference between nutrient contents was statistically significant for all elements (P < 0.05).

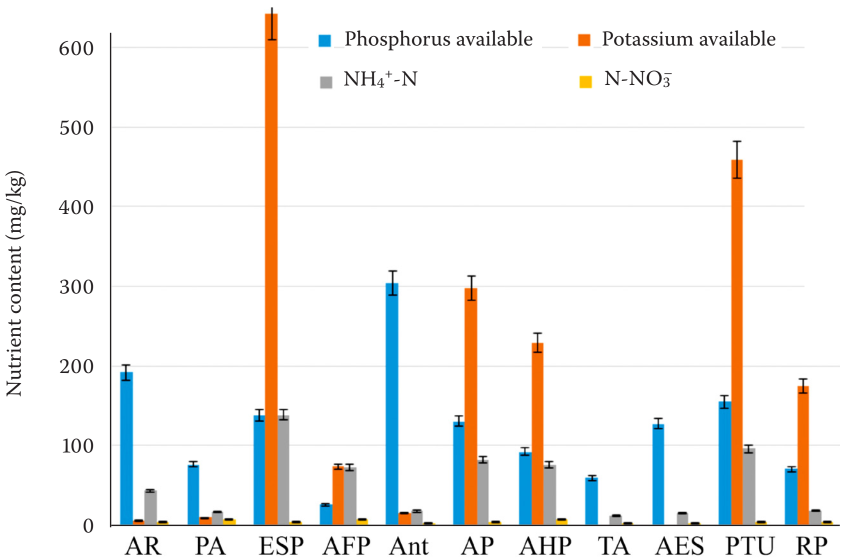

Figure 4. Nutrient content in topsoils of studied islands (for the soil types abbreviation see Table 1)

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CONCLUSIONS

Lands of the Gulf of Finland islands are characterised by a wide soil diversity at different development stages– a predominance of shallow soils – Lithosol (Leptosol) and Petrozem (Arenosol).

The carbon content showed relatively high variability due to different rates of former anthropogenic soil fertilization and the time since the land was last used. Topsoil are characterised by tolerable contamination, contain less P and K and greater content of NH_4^+-N and N-NO_3^- than fallow non-island soils of the Leningrad region.

Due to a decline in agricultural production and cessation of measures to maintain and restore soil productivity, many agricultural soils have acquired signs of irreversible degradation. The study of the environmental soil state of Gulf of Finland islands is of great importance for both understanding pedogeochemical processes in anthropogenic ecosystems and for solving practical problems related to environment and human health protection.

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