Agroecological assessments of arable and post-arable soils and trends of the post-agrogenic evolution of soils over a 30-year-long period under conditions of changing climate in the northern part of the Upper Volga Region, Russia

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Abstract. A potential level of agricultural productivity of formerly arable soils was assessed in a case study within the Poshekhonsky District of the Yaroslavl Oblast, Russia, with the use of an actualized soil-ecological index (SEI). This index showed low and medium fertility levels in most of the studied arable soils during the period of 1988–1990, which was followed by agricultural abandonment of many arable lands. The re-assessment of post-arable varieties of the same soils in 2019 allowed us to identify multidirectional trends of evolutionary changes in soil properties over the three decades. Post-arable soils on loamy parent materials were characterized by the development of stable hydromorphic features, dehumification, a sharp decline in the supply of available nutrients and occasionally an acidification of humus horizons, which was reflected in the reduction of SEI values by 1.1–1.9 times over the study period. Post-arable sandy soils, on the contrary, were characterized by a predominance of progradation processes associated with increasing humus contents and decreasing acidity levels. The post-agrogenic evolution of soils including the development of new soil properties should be taken into account in agroecological assessments and prognoses of the agricultural production potential of soils under conditions of changing climate.

1. Problem formulation
An analysis of potential agricultural resources of post-arable (formerly ploughed) soils of agriculturally abandoned lands within the boreal forest belt (non-Chernozem) regions of Russia and an identification of trends of evolutionary changes in soil morphology and properties during the post-agrogenic period require knowledge of (1) comprehensive original characteristics of arable soils and (2) adequate, balanced and verified approaches to the assessment of changes in the potential soil fertility following the agricultural abandonment of such soils. Regarding the first aspect, we studied the morphology and properties of arable soils within a period of 1988–1990 and their post-arable equivalents in 2019. Regarding the second aspect, we determined the agricultural production potential in arable and post-arable soils on the basis of the soil-ecological index (SEI) [1], which is an integral assessment criterion of the soil quality calculated with the use of edaphic (E), climatic (C) and agrochemical (A) components. Methodologically, it was important that C-component values were determined by us for two periods of equal duration (1961–1990 and 1991–2018, as further explained in Methods) on the basis of combined...
data from nearby meteorological stations, which ensured the calculation of highly informative and reliable SEI values.

Modern climate change is a part of the human-induced change of the environment. Due to close relationships between physical processes in the atmosphere and on the land surface, global warming induces changes in not only the air temperature and the hydrological cycle, but also in many other components of the environment such as the soil cover. Those changes result in new trends of the development of edaphic conditions. It should be emphasized that the modern climate change has an uneven distribution over the geographical space, with certain regional differences [2, 3]. In addition, consequences of global warming are reflected in changes in seasonal values of meteorological parameters, which should also be taken into account in studies on responses of soils to current and future changes of the climate [4, 5].

The aim of the present study was to conduct agroecological assessments of arable and post-arable soils based on the SEI-Method and trends of the post-agrogenic evolution of soils over a 30-year-long period under conditions of changing climate in the northern part of the Upper Volga Region, Russia.

2. Methods of the study

The soil-ecological condition of arable lands was assessed prior to the agricultural reforms on the basis of a case study on automorphic arable soils within the interfluve of the Sheksna and the Kostroma rivers corresponding to the Poshekohnsky District in the Yaroslavl Oblast (figure).

Figure. Location of the studied area (source: https://earthexplorer.usgs.gov/).

Basic morphogenetical and analytical characteristics of agricultural soils were carried out by us within the framework of a large-scale soil survey during the period of 1988–1990, when 159 profiles of soddy-podzolic soils under the agricultural land use of different intensities were described according to the Classification and diagnostic system of soils of the USSR [6]. Those soils were formed on different types (from loamy sands to medium loams) of Quaternary parent materials, some of which had lithic discontinuities.
Values of the climatic component of the SEI were calculated using the standard observation data (air temperatures and precipitation) of the meteorological stations of Rybinsk and Vologda located at southwestern and north-eastern margins of the study area, respectively. For each station, we calculated the following C-parameters: precipitation-to-evaporation ratio, continentality index and the sum of air temperatures above 10 °C. Meteorological data for the periods of 1961–1990 and 1991–2018 were used in calculations of C-components of the SEI of arable and post-arable soils, respectively.

The methodological approach to determination of C-components of the SEI was predetermined by a three-decade interval between soil surveys of 1988–90 and 2019. Thirty years is the duration of a climate assessment interval recommended by the World Meteorological Organization (WMO) [7, 8]. For example, the period of 1961–1990 coincides with the WMO climatological normal interval [7]. Therefore, the adopted approach allowed us to characterize pedogenetic processes triggered by climate change.

Linear trends of air temperature and precipitation within consecutive periods of 1961–1990 and 1991–2018 and the total period from 1961 to 2018 were analyzed using the method of least squares. The statistical significance of these linear trends was determined following recommendations by I.I. Polyak [9], where the 95% significance level is established for the hypothesis of existence of a linear trend. If an estimated linear trend is insignificant with 95% probability, then it is defined as a tendency with either plus or minus sign.

3. Results and discussion
A comparison a two consecutive periods of 1961–1990 and 1991–2018 showed that the rate of increase in the mean annual temperature has doubled over the last three decades and reached 0.6 °C/10 years. Greatest contributions to the change in the mean annual temperature were made by risen temperatures in winter and spring, with less significant increases in summer and autumn temperatures, which agrees with results of earlier assessments [10]. Mean temperatures of winter months increased by 1.2–2.6 °C and the transition of mean daily temperature over 0 °C in spring shifted to almost a week earlier date, with insignificant changes in autumn. Extreme values of climatic parameters are very important indicators of modern climate change within a region [11]. Our analysis of maximal air temperatures in the study area revealed their increase in March, July and December, with insignificant changes in other months within the period of 1991–2018. Changes in minimal temperatures were more notable, as winters became much warmer. Such low mean monthly temperatures as −24.5 °C in January and −17.9 °C in February were recorded during the earlier period, but did not occur for the recent three decades. As a result, the annual pattern of air temperature dynamics has changed. The coldest month of the year has shifted from January to February and March in 4–5% of studied cases. July has remained the warmest month, but its mean temperature raised by 2 °C within the last three decades.

The mean annual precipitation within the territory of Russia increases for the last 40 years at a mean rate of 2.1% in 10 years [12]. Within the study area, the mean annual precipitation changed insignificantly, but the distribution of precipitation over seasons was characterized by the shift of the maximal precipitation from July to August, according to the meteorological data from both Rybinsk and Vologda stations.

The values obtained for C-parameters of the SEI were used in the analysis of climate change within the studied Upper Volga Region. A comparison of the two periods (1961–1990 and 1991–2018) showed that the precipitation-to-evaporation ratios and the continentality indices decreased by 1 and 5%, respectively, though change in the mean annual precipitation was insignificant. At the same time, the annual sum of air temperatures above 10 °C (Σt ≥ 10°) increased from 1606 to 1721 °C. Such an increase in the sum of active temperatures was the main contribution to the increase in the value of the resulting C-component of the SEI from 6.3 to 6.7.

As a result of the agroecological assessment based on the SEI values, the studied arable soils were ranked into four groups (table 1). It was established that most of agricultural soils of the Poshekonsky District during the last years of the Perestroika period belonged to the first two groups corresponding to generally low and medium
levels of potential fertility (table 1). Soil genetic properties were reflected in the composition of each group, i.e., the degree of podzolization development decreased with the increase in SEI values from group 1 to group 4, which was also accompanied by the decrease in soil diversity. Considering that the management of arable soils within the study area was generally the same in terms of measures applied for maintaining soil fertility, such ranking of SEI values reflected initial differences in potential fertility levels of the studied soils.

Table 1. Soil grouping based on the SEI values determined as a result of the soil survey within the Poshekhonsky District in the Yaroslavl Oblast in 1988–1990.

| Soil groups | SEI values | Total number of soil varieties | Soil differentiation based on degrees of podzolization\(^a\), % of the group |
|-------------|------------|-------------------------------|--------------------------------------------------------------------------------|
|             |            |                               | weak | moderate | strong |
| 1           | 20–29      | 16                            | 2    | 23       | 65     |
| 2           | 30–39      | 24                            | 11   | 47       | 42     |
| 3           | 40–49      | 11                            | 24   | 41       | 35     |
| 4           | 50–60      | 9                             | 56   | 22       | 22     |

\(^a\) The degree of development of podzolization process was determined by the depth of the lower boundary of the eluvial/subeluvial horizon of soil, according to [6].

According to the Classification and Diagnostic System of Russian Soils [13], the first group was dominated by agrosoddy deep- and shallow-podzolic loamy soils, which were formed mainly on parent materials with lithic discontinuities as well as on lithologically homogenous mantle loams and moraine deposits. The second group included agrosoddy shallow-podzolic soils formed on parent materials with and without lithic discontinuities. The third group corresponded to agrosoddy shallow-podzolic soils mostly on lithologically homogenous parent materials, some of which were calcareous. The fourth group unified agrozems and agrosoddy shallow-podzolic soils on parent materials with and without lithic discontinuities including calcareous mantle loams and moraines.

In addition to the differences in soil genetic characteristics predetermined by the C-component of the SEI, the studied soils were also differentiated on the basis of E- and A-components of the SEI that were calculated on the basis of deviations of properties of the studied soils from their average values within the natural zone of taiga (table 2).

Table 2. Physicochemical and chemical properties of automorphic arable soils within the Poshekhonsky District in the Yaroslavl Oblast.

| Soil groups | SEI values | Humus content, % | pH\(_{KCl}\) | P\(_2\)O\(_5\) mg/100 g | K\(_2\)O mg/100 g | n |
|-------------|------------|------------------|-------------|----------------------|------------------|---|
| 1           | 20–29      | 1.22±0.02        | 4.92±0.12   | 7.30±1.80            | 7.37±1.07        | 57 |
| 2           | 30–39      | 1.58±0.03        | 5.64±0.16   | 10.55±1.50           | 9.28±1.01        | 74 |
| 3           | 40–49      | 2.11±0.20        | 5.76±0.36   | 12.94±1.71           | 15.22±2.59       | 19 |
| 4           | 50–60      | 2.63±0.17        | 6.20±0.29   | 16.29±4.17           | 16.79±4.70       | 9  |

The humus content, being an important parameter of the E-component of the SEI, was very low in groups 1 and 2 and low in groups 3 and 4. According to the pH\(_{HCl}\), soils of group 1 were acidic and soils of other groups – weakly acidic. The supply of essential nutrients for plants was very low in all groups (table 2). Therefore, according to the Russian standards [14], almost all automorphic arable soils studied by us within the Poshekhonsky District by 1990 belong to arable soils under generally low-intensive use.

We calculated the shares of each component in the resulting mean SEI values for each group (table 3).
Table 3. Mean values of SEI and its edaphic (E), climatic (C) and agrochemical (A) components and their percentages of the mean SEI values of each group of arable soils.

| Soil groups | Mean SEI values | Mean values of SEI components | SEI component percentage (%) of the mean SEI value |
|-------------|-----------------|-------------------------------|---------------------------------------------|
|             | E   | C   | A   |                  | E  | C  | A  |
| 1           | 26.5| 4.98| 6.3 | 0.85            | 41.0|52.0|7.0 |
| 2           | 34.6| 5.65| 6.3 | 0.98            | 43.6|48.8|7.6 |
| 3           | 43.5| 6.31| 6.3 | 1.10            | 46.0|46.0|8.0 |
| 4           | 54.4| 6.86| 6.3 | 1.26            | 47.6|43.7|8.7 |

Under similar temperature and precipitation conditions, i.e., the similar C-component value for the whole data set, an increase in mean SEI values in groups 1 to 4 mainly resulted from the contribution of the E-component and, to lesser extent, the A-component. In groups 1 and 2, the A-component had values of less than one, which means that those soils had low levels of inorganic nutrients. In our opinion, the A-component makes only a small contribution to the mean SEI value and reflects the effective, not a potential fertility of soil. The potential fertility of the studied soils mainly depends on their lithological basis (parent materials), which predetermine soil texture, hydrological regime, nutrient supply and the degree of development of podzolization processes. It should be noted that most significant contributions of the E-component are associated with soil groups 3 and 4 with high SEI values, while groups 1 and 2 with low SEI values are characterized by the prevalence of C-component with lesser contribution of the E-component.

Data from two observation periods with an interval of three decades were used by us for the identification of post-agrogenic evolutionary changes in the studied soils connected with regionally-specific trends of global warming and changes in the hydrological cycle. In 2019, the majority of formerly arable soils within the Poshekonsky District were abandoned for periods from 7 to 30 years and colonized by meadow communities, however, some of the soils remained under arable use. Therefore, most of the studied soils underwent a change in the land use during the 30-year interval between our observations, which was also considered as a second half of the global climatic trend. The first summary of the results obtained on selected soil pits is presented in table 4. Judging from even a limited number of data, there are clear trends of changes in properties of post-arable soils that are reflected in SEI values.

In post-arable loamy soils, SEI values significantly decreased (by 1.1–1.9 times) as compared to their arable condition, which was often, associated with a gradual loss of soil fertility after the agricultural abandonment. Although values of the C-component increased over the three decade period (table 4), the abandonment of formerly arable loamy soils resulted in the development of degradation processes including dehumification, a sharp decline in the supply of available nutrients for plants and, in some cases, acidification of the former plough layers. In addition, hydromorphic features were observed in all studied post-arable loamy soils within the Poshekonsky District, despite the fact that their arable equivalents during our previous survey were characterized as automorphic soils, i.e., free-drained soils unaffected by groundwater, as they were formed in autonomous (interfluve) topographic positions.

The deterioration of the agrochemical properties of post-arable loamy soils is due to the cessation of organic-mineral fertilizers and liming. This process is accompanied by stable morphological features of gleization, against the background of changed climatic conditions, which also contribute to the manifestation of degradation processes in the initially automorphic soils.

Hydromorphic features that resulted from waterlogging of modern soils were observed by us at macro-, meso- and micromorphological scales. In humid climate, waterlogging negatively affects the agroecological soil quality, i.e., decreases the soil quality grade, according to the soil assessment model based on SEI calculations [1].
Table 4. Physicochemical and chemical properties and SEI values of the studied arable soils (in 1988–1990) and their post-arable equivalents (in 2019).

| Soil pit<sup>a</sup> | Land use<sup>b</sup> | Humus, % | pH<sub>KCl</sub> | P<sub>2O5</sub> mg/100 g | K<sub>2O</sub> | Components of SEI | SEI |
|---------------------|----------------------|----------|----------------|----------------|---------|-----------------|-----|
| I-79-19             | post-arable, 12–15   | 2.26     | 5.1            | 4.5            | 4.7     | 5.2             | 6.7 | 0.8  | 27.9 |
| I-79                | arable               | 3.09     | 5.8            | 13.5           | 16.7    | 7.2             | 6.3 | 1.2  | 54.4 |
| Z-37-19             | post-arable, 7–10    | 3.32     | 5.7            | 18.3           | 7.5     | 6.8             | 6.7 | 1.1  | 50.1 |
| Z-37                | arable               | 3.04     | 6.3            | 22.9           | 9.0     | 7.2             | 6.3 | 1.2  | 54.4 |
| R-131-19            | post-arable, 20–25   | 3.43     | 5.9            | 12.4           | 10.6    | 5.5             | 6.7 | 1.1  | 40.5 |
| R-131               | arable               | 2.75     | 5.9            | 14.7           | 10.7    | 5.5             | 6.3 | 1.1  | 38.1 |
| ZI-223-19           | arable               | 1.89     | 5.5            | 9.8            | 6.9     | 6.4             | 6.7 | 0.9  | 38.6 |
| ZI-223a-19          | post-arable, 30      | 2.12     | 6.0            | 14.6           | 8.8     | 6.5             | 6.7 | 1.1  | 47.9 |
| ZI-223              | arable               | 1.41     | 5.0            | 13.9           | 12.7    | 5.5             | 6.3 | 1.0  | 34.7 |
| ZI-21-19            | arable               | 2.00     | 4.5            | 12.9           | 13.2    | 6.2             | 6.7 | 0.9  | 37.4 |
| ZI-21               | arable               | 2.64     | 6.1            | 25.1           | 5.8     | 7.0             | 6.3 | 1.2  | 52.9 |
| V-161-19            | post-arable, 7–10    | 1.46     | 4.6            | 3.6            | 4.3     | 5.3             | 6.7 | 0.8  | 28.4 |
| V-161               | arable               | 2.40     | 4.3            | 5.6            | 6.1     | 6.8             | 6.3 | 0.8  | 34.3 |
| C-175-19            | post-arable, 20      | 1.95     | 4.6            | 7.5            | 4.5     | 5.0             | 6.7 | 0.8  | 26.8 |
| C-175               | arable               | 1.74     | 4.5            | 10.1           | 6.8     | 6.0             | 6.3 | 0.9  | 34.0 |
| C-41-19             | post-arable, 15      | 1.97     | 4.9            | 4.7            | 5.5     | 5.9             | 6.7 | 0.8  | 31.6 |
| C-41a-19            | post-arable, 20–25   | 2.06     | 4.2            | 3.1            | 4.4     | 6.2             | 6.7 | 0.7  | 29.1 |
| C-41                | arable               | 1.98     | 4.8            | 8.9            | 7.9     | 6.2             | 6.3 | 0.9  | 35.2 |

<sup>a</sup> Digits 19 in a pit number mean that the soil was studied in 2019.

<sup>b</sup> Digits following the words ‘post-arable’ specify the period of abandonment. Soil names (according to WRB [15]): I-79-19 – Stagnic Endocalcaric Retisol (Siltic, Anoaric, Cutanic, Humic); I-79 – Endocalcaric Retisol (Siltic, Aric, Cutanic, Humic); Z-37-19 – Stagnic Endocalcaric Retisol (Abruptic, Siltic, Anoaric, Cutanic, Humic, Raptic); Z-37 – Endocalcaric Retisol (Abruptic, Siltic, Aric, Cutanic, Humic, Raptic); R-131-19 – Cambisol (Arenic, Anoaric, Humic); R-131 – Cambisol (Arenic, Aric, Humic); ZI-223a-19 – Chromic Cambisol (Geobructive, Arenic, Anoaric); ZI-223 and ZI-223-19 – Chromic Cambisol (Geobructive, Arenic, Aric); ZI-21-19 and ZI-21 – Glossic Retisol (Abruptic, Siltic, Aric, Cutanic, Raptic, Humic); V-161-19 – Glossic Stagnic Endocalcaric Retisol (Siltic, Anoaric, Cutanic); V-161 – Glossic Endocalcaric Retisol (Siltic, Aric, Cutanic); C-175-19 – Glossic Stagnic Retisol (Abruptic, Siltic, Anoaric, Cutanic, Raptic); C-175 – Glossic Retisol (Abruptic, Siltic, Aric, Cutanic, Raptic); C-41a-19 – Glossic Stagnic Endocalcaric Retisol (Abruptic, Siltic, Anoaric, Cutanic, Raptic); C-41-19 – Glossic Stagnic Endocalcaric Retisol (Abruptic, Siltic, Aric, Cutanic, Raptic).

On the contrary, in light-textured soils on unconsolidated parent materials, the agricultural abandonment resulted in the development of progradation processes such as humus accumulation and increase in pH, which was reflected in the increase in SEI values, despite that there were slight decreases in available phosphorus and potassium contents. It should be mentioned that morphological features of gleization were absent from light-textured soils due to their high permeability.

4. Conclusions

Our investigations resulted in the unbiased and detailed assessment of the agroecological quality of arable and post-arable automorphic soils in the north of the Yaroslavl Oblast. The data obtained with a
high spatial resolution served us as a basis for the analysis of changes in soil properties during the post-agrogenic period of 1991–2019, which was accompanied by changes in climatic conditions.

Post-agrogenic changes in soils formed on loamy and sandy parent materials had multidirectional trends associated with degradation processes in loamy soils and progradation processes in light-textured soils, which were reflected in the calculated values of the soil-ecological index.

A combined analysis of changes in soil properties and climatic parameters can help in assessments of rates of pedogenic processes and levels of soil fertility and serve as a basis for simulation modelling of soil climate in perspective. Specific characteristics of the post-agrogenic evolution of soils and the development of new soil properties should be taken into account during agroecological soil assessments and prognoses of the agricultural production potential of soils under conditions of changing climate.

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References
[1] Shishov L L, Durmanov D N, Karmanov I I and Efremov V V 1991 *Theoretical basis and methods of management of soil fertility* (Moscow: Agropromizdat) p 304 (in Russian)
[2] Assessment report on climate change and its consequences in Russian Federation. General Summary 2008 (Moscow: Roshydromet) p 24
[3] Pachauri R K and Meyer L A (eds) 2014 Climate change 2014: Synthesis report. *Contribution of working groups i, ii and iii to the fifth assessment report of the intergovernmental panel on climate change* (Geneva: IPCC) p 151
[4] Sherstyukov B G 2008 *Regional and seasonal trends of the modern climate change* (Obninsk: GU VNIIGMI-MTsD) 300 p (in Russian)
[5] Global warming of 1.5°C 2018 Summary for policy makers available at: http://report.ipcc.ch/sr15/pdf/sr15_spm_final.pdf [Accessed 25.10.2020]
[6] Classification and diagnostics of soils of the USSR 1977 (Moscow: Kolos) 223 p (in Russian)
[7] Calculation of monthly and annual 30-year standard normals WMO/TD-No.341, WCDP 1989 (10) 12
[8] *WMO Guidelines on the calculation of climate normals* WMO-No.1203 2017 29
[9] Polyak I I 1975 An assessment of a linear trend of temporal meteorological sequences *Reports of the main geophysical observatory* (Trudy GGO) (364) pp 51–5 (in Russian)
[10] Gruza G V and Ran’kova E Ya 2012 *Observed and expected changes in the climate of Russia: air temperature* (Obninsk: FGBU VNIIGMI-MTsD) p 194 (in Russian)
[11] Alexander L V and et al. 2006 Global observed changes in daily climate extremes of temperature and precipitation J. Geophys. Res. 111 22
[12] *Report on climate risks in the Russian Federation* 2017 (Saint-Petersburg) p 106
[13] Shishov L L, Tonkonogov V D, Lebedeva I I and Gerasimova M I 2004 *Classification and diagnostic system of Russian soils* (Smolensk: Oikumena) p 342 (in Russian)
[14] Frid A S, Kuznecova I V, Koroleva I E, Bondarev A G, Kogut B M, Utkaeva V F and Azovceva N A 2010 Zonal-provincial regulations for man-made changes in agrochemical and physical characteristics of main arable soils within the European part of Russia Methodological recommendations (Moscow: Dokuchaev Soil Science Institute) p 176 (in Russian)
[15] IUSS Working Group WRB 2015 *World Reference Base for Soil Resources. International soil classification system for naming soil and creating legends for soil maps. World soil resources reports* (Rome: FAO) p 181