Agroecological assessment of soils in the foothills of Khakassia

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Abstract. The agroecological assessment of the chernozems of the arable land calculating the soil-ecological index (SEI) was carried out according to I. I. Karmanov’s method. It is found that the agroclimatic potential (AP) is increased in the forest-steppe foothills (5.6–5.9). It is average in the steppe foothills of the Western Sayan mountains (4.7–4.9) and low in the steppe of the Kuznetsky Alatau (4.1–4.2). The agroecological assessment of soils is closely related to AP, except the soils of the forest-steppe foothills of the Kuznetsky Alatau. SEI is changed in the following sequence. The podzolized and leached chernozems of the foothills of the Western Sayan and the ordinary chernozems of the forest-steppe spurs of the Kuznetsky Alatau have SEI averaged 56 points > the ordinary chernozems of the Western Sayan steppes – 54 > the ordinary chernozems of the forest-steppe foothills of the Kuznetsky Alatau – 49 > the southern chernozems of the Kuznetsky Alatau – 32. In comparison with the normal soils, the score for the weakly degraded soils decreases by 1.2–1.5 times, for the medium degraded soils – by 2–3 times, for the highly degraded soils – by 4–6 times.

1. Introduction

Increasing soil-ecological problems of the agricultural land has led to the need for more differentiated approach for using land resources and the adaptation of agricultural production to the landscape conditions. The solution of this problem can be a preliminary agroecological assessment and land grouping, the methodology of which is described in the guide [1]. This is detailed study of the soil condition, its productive capacity, which provides opportunities for determining the permissible anthropogenic load on it and its future use in agriculture [2].

Soil-ecological principles of land resource assessment are currently very actual due to the global warming and some negative processes connected with it. On the territory of the Republic of Khakassia (South Central Siberia) during the period from 1941 to 2000, the average annual air temperature increased by 0.02 °C/year in the forest-steppe and by 0.04 °C – in the steppe [3]. In general, the climate has warmed by 1.2 °C in 60 years, which, on the one hand, is a very desirable factor for increasing the bioclimatic potential of the region. On the other hand, such changes are accompanied by the increase in droughts, extreme temperature differences, and the frequency of winter thaws. The most dangerous for the growth of agricultural crops are soil droughts. In the dry steppe of Khakassia over the period from 2002 to 2012, their frequency increased: in May – by 54.5%, in June – by 45.4%, in July – by 27.3% [4], which limits the effective agriculture here. The problems of managing the productivity of agroecosis and soil fertility have become significantly more complex. Therefore, the main production of grain crops should be conducted in the foothills under more favorable climatic conditions taking into account the agroecological assessment of soils and the stability of agricultural landscapes.
Currently, different countries have quite great experience in soil assessment. Methodically the most developed and widely used in all world countries are the approaches based on the method of evaluation of lands FAO [5], as well as soil-ecological approaches to soil assessment developed by Russian researchers [6–11], which may allow to conduct a detailed assessment of soil condition of agricultural landscapes. An integral quantitative expression of the qualitative state of soils is the assessment of the level of agro-ecological potential based on the soil-ecological index and its modification – the soil-agro-climatic index (SACI) [12]. SACI refers to multiplying indexes widely used in the world practice of land valuation. For example, it is one of the most famous SIR indexes (Storie index rating) abroad. While comparing the SACI index to SIR on condition of maintaining versatility and simplicity, it can be found that soil and climate aspects are significantly enhanced, natural conditions for different regions of Russia are detailed, the main agricultural crops are differentiated, which significantly increases the accuracy and efficiency of the assessment [13].

The soil-ecological index (SEI) is one of the most widely used estimation indicators of soil cover. SEI is used for the evaluating both individual soil types and soil combinations, as well as for land masses with complex structures of soil cover. In agro-ecological and cadastral assessment of soil cover, SEI has a number of advantages over other assessment criteria. Firstly, SEI is an integral quantitative indicator, since it takes into account a wide range of soil and climate characteristics that determine the agro-ecological potential of soils and soil cover (coefficients of moisture and continentality, the soil density in a meter layer, the granulometric composition of soils and rocks, and some other agro-ecological significant characteristics of soils). Secondly, in contrast to regional assessment systems, with the help of SEI, it is possible to compare the productive capacity (agroecological potential) of the evaluated soils in a single all-Russian scale. However, the regional characteristics of agro-ecological conditions of agricultural lands have yet to be fully studied, the data of soil surveys conducted in Khakassia in the 50–90s of the last century are outdated, and there is a need for new up-to-date information on the agroecological assessment of soils. The urgency of this problem has determined the purpose of our work – to assess the agroecological potential of chernozems in the foothills of Khakassia on the basis of developed methods, which will increase the efficiency of using soil resources and minimize the degradation processes.

2. Objects and methods of research

According to natural conditions, the territory of Khakassia is heterogeneous and belongs to three large geographical areas: the Western Sayan, Kuznetsky Alatau and Minusinskaya basin, which are connected with each other as separate parts of the Altai-Sayan mountain system [14]. The objects of the research were arable and post-agrogenic soils of the agricultural part of the foothills of the Western Sayan and Kuznetsky Alatau. In the system of soil-geographical zoning, the research area is assigned to the Minusinsk province. Soils belong to the facies subtypes of moderate deep and long-term freezing soils [15], which are mainly represented by chernozems of different subtypes (80%). The leached chernozems predominate in the forest-steppe areas of the Western Sayan foothills, while ordinary chernozems – in the foothills of the Kuznetsky Alatau. The ordinary and southern chernozems.

The structure of the soil cover was determined by the morphological features of soil sections. The genetic belonging of soils was determined according to the classification [16, 17]. Soil samples were taken from the genetic horizons of the soil profile for the laboratory analysis and subsequent clarification of the diagnosis. The soil analysis was carried out according to generally accepted methods: the granulometric composition – by the pipette method including the soil treatment with sodium pyrophosphate, the content of humus – according to I. V. Tyurin, the determination of mobile compounds of phosphorus and potassium modified by CINAQ – according to F.V. Chirikov (in the podzolized and leached chernozems) and according to B.P. Machigin (in the ordinary and southern chernozems), pH (salt and water) – by the potentiometric method. Physical and agro-physical characteristics of soils were determined using the methods described in the manual [18]. The soil density was determined by the N.A. Kachinsky’s cutting cylinder method when 10 cm up to half a meter layers were studied.
The agro-ecological assessment of soils was performed based on the method of I. I. Karmanov with the help of the soil-ecological index (SEI) [9]. Unlike regional assessments, it provides comparable results on a common basis for the entire country. We accepted for 100 points the SEI of chernozems typical for the Krasnodar territory, with favorable climate conditions and agroclimatic potential which are equal to 10, where the sum of temperatures above 10 degrees ($\Sigma t > 10^o$) is 3500; the humidification coefficient is 0.8; the continentality coefficient is 162. The SEI is determined by a set of soil characteristics, modes and a set of landscape and climatic conditions and depends on the variety of soil, differences of which can be observed both between sites and on different territories within the borders of a single site.

3. Results and discussion

3.1. Agroclimatic potential of the foothills of Khakassia
Features of the geographical position of the foothills that affect the agro-ecological assessment of soils and lands are determined primarily by the geological and geomorphological factor (determining the structure of zoning and vertical belt); by the climatic regime (continentality, heat and moisture availability); by the condition of occurrence of soil-forming rocks. Spatial distribution of soils is governed by the laws of vertical zoning and latitudinal zoning.

On a large territory of the foothills of Khakassia, the relief is low-mountain. Agricultural land is located in complex landscapes of hilly plains, where there is a redistribution of moisture due to surface runoff, which is associated with the development of erosion processes. At the same time there are more favorable agro-climatic conditions for the cultivation of grain crops.

Agro-landscapes adjacent to the mountains of the Western Sayan are located in the southern warmer part of the territory of Khakassia in the administrative Tashtypsky and Baysky districts. Agro-landscapes of the foothills of the Kuznetsky Alatau are located in the north western, cooler and arid part of Khakassia (Ordzhonikidzevsky, Shirinsky, and Bogradsky districts). The coefficient of climate continentality (CC) in the foothills varies from sharp to extremely continental (193–217), the moisture coefficient (MC) is insufficiently moistened in the forest steppe (1.02–0.99) and arid in the steppe (0.74–0.82) (table 1).

| Administrative district | Latitude of the area, degree | $\Sigma t > 10^o$ | MC | CC | AP |
|-------------------------|------------------------------|-------------------|----|----|----|
| The foothills of the Western Sayan mountains | | | | | |
| Tashtypsky (forest-steppe) | 52.7 | 1700 | 1.02 | 199 | 5.8 |
| Bey (forest-steppe) | 52.8 | 1800 | 0.99 | 200 | 5.9 |
| Bey (hilly steppe) | 53.0 | 1800 | 0.82 | 200 | 4.9 |
| Bey (flat steppe) | 53.1 | 1900 | 0.79 | 217 | 4.7 |
| The foothills of the Kuznetsky Alatau | | | | | |
| Ordzhonikidzevsky (forest-steppe) | 54.6 | 1600 | 1.01 | 193 | 5.7 |
| Bogradsky (forest-steppe) | 54.4 | 1700 | 0.99 | 206 | 5.6 |
| Bogradsky (hilly steppe) | 54.4 | 1700 | 0.77 | 212 | 4.2 |
| Shirinsky (hilly steppe) | 54.3 | 1700 | 0.74 | 204 | 4.1 |

The agroclimatic potential (AP) of the steppe of the Western Sayan foothills is by 1.1 less than one of the forest-steppe part, and in the arid steppes of the foothills of the Kuznetsky Alatau AP is even lower (1.4 times). The great dryness of the climate of the latter is explained by the main transfer of air
masses from the West. When moving along the Eastern slopes of the Kuznetsky Alatau, they are heated up and as they descend, they have a drying effect on the steppes, so there is less precipitation [20].

Thus, on the totality of the climatic indicators that characterize the agricultural productivity of agricultural landscapes in the foothills of Khakassia, three regions are distinguished. Increased climate potential can be found in the forest-steppe of the foothills (AP 5.6–5.9), average – in the steppe of the foothills of the Western Sayan (4.7–4.9) and low – in the steppe foothills of the Kuznetsky Alatau (AP 4.1–4.2). However, the agro-climatic potential of the foothills of Khakassia is on average two times lower than the base value (AP 10) of the Krasnodar territory, located in the European part of the country.

3.2. Agroecological assessment of soils of the Western Sayan foothills

Agro-soils in the forest-steppe zone of the foothills of the Western Sayan belong to the accumulative-humus division, which includes the type of clay-illuvial chernozems (with subtypes of podzolized and leached soils). The soil-ecological index of their landscape conditions (slope exposure, elementary landscape positions on the slope) changes from 43 to 65 points depending on the soil-forming rocks. The podzolized and leached non-degraded chernozems practically do not differ from each other in terms of fertility, have mainly an average thickness of the humus horizon, the reserves of humus vary from medium to high. The agroecological assessment of soils in the forest-steppe foothills of the Western Sayan is high (the podzolized chernozems have 57 points, the leached ones – 59 points) (table 2). In the podzolized chernozems the acidic soil environment and low rates of mobile phosphorus and potassium compounds reduce the overall environmental assessment of the soil by 12%.

Table 2. Fertility indicators and soil-ecological index of chernozems in the foothills of the Western Sayan (Beysky district, 2018).

| The soil                          | Capacity of the humus horizon, cm | Humus, t/ha layer, cm | Mobile forms of nutrients, mg/kg soil | Physical clay, % | SEI, point |
|-----------------------------------|-----------------------------------|-----------------------|--------------------------------------|------------------|------------|
| Foothill forest-steppe of Western Sayan (Tabatskoe) | Foothill forest-steppe of Western Sayan (Tabatskoe) | Podzolized chernozems | 39 | 0–20 – 231.6 | 59.1 | 87 | 52.1 | 57 |
|                                  |                                   | Leached chernozems    | 46 | 0–20 – 122.4 | 169 | 626 | 48.8 | 59 |
|                                  | Rolling Prairie foothills of the Western Sayan mountains (Bey) | Ordinary chernozems | 33 | 0–20 – 109.8 | 24.7 | 357 | 46.3 | 52 |
|                                  |                                  | Southern chernozems   | 30 | 0–20 – 95.8 | 15.5 | 359 | 38.4 | 39 |
| Foothill steppe valley of the Western Sayan (Novokurskoe) | Foothill steppe valley of the Western Sayan (Novokurskoe) | Ordinary chernozems | 45 | 0–20 – 140.1 | 66.8 | 512 | 57.6 | 56 |

In the forest-steppe on the slopes of the southern exposure the ordinary chernozems with medium and high fertility potential (SEI of 43–52 points) are developed. In the foothill belt of the steppe the fertility of ordinary chernozems decreases, which is connected with the deterioration of moisture content (AP 4.9–4.7). Thus, in the non-degraded chernozems of ordinary heavy loam, the humus stock in the layer of 0–20 cm is average (110 t/ha – in the hilly steppe and 140 – in the plain). Despite the increased continental climate of the plain (winter is colder and summer is hotter) compared to the hilly part of the steppe, their agroecological assessment is higher by 4 points. Accumulative processes occur more
intensively in the flat part of the steppe, which is apparently facilitated by better heat supply and longer biological activity of the soil.

During the transition from the ordinary to southern chernozems there is a further significant decrease in the soil fertility, which is associated with the climatic conditions of the topography (in the present steppe they occupy mainly the slopes of the southern and southwestern exposures). Humus reserves in the southern chernozems are low with an average agroecological score of 39 points. The SEI of degraded chernozems of different subtypes varies from 10 to 52 points. The assessment of soils is reduced by 1.2–1.5 times for weakly degraded soils, by 2–3 times for medium degraded soils and by 4–6 times for highly degraded soils compared to normal soils.

3.3. Agroecological assessment of the foothills of the Kuznetsky Alatau

In the agro-landscapes of the forest-steppe part of the foothills of the Kuznetsky Alatau a significant part of open area is characterized by the dominance of the ordinary chernozems and the subordinate development of the leached chernozems in the forest. In the low-mountain forest steppe spurs of the Kuznetsky Alatau (Bogradsky district), the gentle northern and northeastern slopes are occupied by medium thick and powerful, heavy-loamy ordinary chernozems developed on the yellow-brown rocks. These soils have high fertility potential. The SEI is 59 points with account of the climatic, agrochemical, soil indicators and landscape features of the territory (table 3).

Table 3. SEI of chernozems on gentle slopes of different expositions in the foothills of the Kuznetsky Alatau, in points (Bogradsky district, 2015).

| Forest-steppe of the spurs of the Kuznetsky Alatau | Hilly steppe |
|---------------------------------------------------|-------------|
| Ordinary chernozems                               | Southern chernozems |
| Expositions and parts of slopes                   |             |
| South-Eastern                                    | South-Eastern |
| lower part – 59.4                                | upper – 24.7 |
| middle part – 58.7                               | middle – 20.8 |
|                                                   | lower – 32.1 |

In the hilly steppe low humus reserves are found in the southern medium-loamy chernozems developed on the red-colored rocks, and in the light loamy soils on the southern slope humus reserves are even lower (by 1.7 times). In the soil cover of the transit positions of slopes, the average degree of soil degradation reaches 25–50%, on the slope of the southern exposure there are local spots of a strong degree. On the flat, straight slopes the soil fertility usually gradually increases from top to bottom, but it often occurs that during summer rainstorms the second transit part is destroyed more.

Thus, on the slope of the South Eastern exposure in the transit part, the humus stock is low (in the 0–50 cm layer it was 79.4 t/ha on the first part and 66.5 – on the second part) and in the eluvial-accumulative (lower) part the humus stock is medium (114 t/ha).

Then non-degraded soils are characterized by the maximum indicators of the SEI on the lower part of the slope while the salinization of the lower horizons in the soil profile reduces this indicator by 3 points. The minimum point of the SEI is in the mid-transit part of the slope, where the soil has been exposed to a joint manifestation of water and wind erosion. In the agroecological soil assessment of the field, taking into account the entire complex of soils, the score of one hectare is significantly reduced, especially in the lands of the southern exposure (15 points), these lands are light loam, structure less, potentially dangerous to deflation and erosion.

In the forest-steppe zone of the Northern part of the territory of Khakassia (Ordzhonikidzevsky district), the agro-ecological potential of ordinary chernozems is medium. The humus content on the slope of the North-Eastern exposure was 4.7% in the arable layer and 5.1% in the sub-arable layer, in similar conditions in the steppe part – 5.7 and 5.1%, respectively. When converted to humus reserves, they were equal, at the level of the average value (118 t/ha – in the 0–20 cm layer and 248 – in the 0–50
cm layer). Their mobile phosphorus content is low, and their potassium content is medium. The soil medium is alkaline throughout the entire profile (pH$_{H_2O}$ 7.8–8.5). The agroecological assessment of soils was 47.7–50.7 points. The factors limiting agriculture are: weak heat supply of the territory, stony slope lands, soil susceptibility to erosion processes (fallow lands have a small thickness of humus horizons, low content of nutrients in the soil – nitrogen and phosphorus). The SEI of ordinary chernozems of various degrees of degradation varies from 41.9 to 15.4 points.

Thus, ordinary chernozems in the forest-steppe of the Kuznetsky Alatau are characterized by an average SEI, and in the low-mountain part of its spurs, the ordinary chernozems have a high fertility potential. In the hilly steppe the soils of the Kuznetsky Alatau are characterized by low agroecological potential, they are weakly stable to the negative processes of erosion and deflation. The soil protection of the territory should be mandatory for these lands, with differentiated usage of different parts of the slopes.

4. Conclusion
In the forest-steppe and steppe zones of the foothills of Khakassia the agroecological assessment of arable land was carried out for its rational use. Agricultural land is located in the complex landscapes of hilly plain and gently rugged plains, where there is a redistribution of moisture due to surface runoff, which is associated with the development of erosion processes. Undisturbed and degraded soils on the slopes of different exposures and agroclimatic indicators were evaluated. Three districts were identified according to the combination of similar climatic indicators that characterize the agricultural productivity of the agricultural landscapes of the foothills of the Western Sayan and Kuznetsky Alatau. Forest-steppe territories of the foothills have an increased agro-climatic potential (AP 5.6–5.9), the steppes of the Western Sayan foothills have an average potential (AP 4.7–4.9) and the steppe foothills of the Kuznetsky Alatau – a low potential (AP 4.1–4.2).

A close relationship with climate conditions and soil fertility is determined in the foothills of the Western Sayan and the spurs of the Kuznetsky Alatau with the best heat supply. In the forest-steppe of the Kuznetsky Alatau the soil fertility does not match the climate potential due to the shorter and cooler growing season. The average indicators of the agroecological assessment of the chernozems decrease in the following sequence. The podzolized and leached chernozems of the foothills of the Western Sayan, as well as the ordinary chernozems of the forest-steppe spurs of the Kuznetsky Alatau have SEI averaged 56 points; the ordinary chernozems of the Western Sayan steppes – 54 points; the ordinary chernozems of the forest-steppe foothills of the Kuznetsky Alatau – 49 points; the southern chernozems of the Kuznetsky Alatau – 32 points. The slope lands of the arid steppe of the foothills of the Kuznetsky Alatau were significantly degraded, especially on the light soils of the southern exposure. The agroecological assessment of degraded chernozems of different subtypes varies from very low to medium (SEI of 10–52). In comparison with normal soils, the score decreases by 1.2–1.5 times on the weakly degraded soils, by 2–3 times on the medium degraded and by 4–6 times on the highly degraded soils.

Thus, the agroecological assessment of arable soils in the foothills of Khakassia will allow to increase the degree of soil protection: to use differentially the slope lands, taking into account the soil protection measures, to transform the disturbed lands into natural forage lands with the aim of restoring the soil fertility.

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