
REGIONAL PROBLEMS OF NATURE STUDY
AND USE OF NATURAL RESOURCES

Soils of Southern Cisbaikalia: Diversity and Spatial Distribution Patterns

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Abstract—Soil studies were conducted in Southern Cisbaikalia. It has been established that climate and topography significantly affect the soil cover diversity and spatial distribution at the macro- and mesolevel. The complex geological structure, uneven age, and variety of bedrocks, as well as the composition and weathering degree of soil parent rocks, determine the distinct features of soils in the study area. As an example, the development of residual-calcareous brown forest soils is confined to outcrops of highly carbonaceous Cambrian rocks. At the microlevel, the soil cover structure is determined by the paleocryogenic Late Pleistocene microrelief. Its hummocky–pitted forms contribute to the differentiation of soil formation processes, thus, increasing the soil cover sophistication. Contrasting soil microcombinations are represented by complexes of automorphic autonomous soils on hummocky polygons and semihydromorphic heteronomous soils in cryogenic wedge-shaped structures (depressions). On hummocky polygons, the soil profile is formed in undisturbed ground masses, which is consistent with the postlithogenic soil formation type; while removals of the soil materials that occur on a regular basis indicate the denudation pedogenesis model. In depressions, the soil profile is formed in redeposited soil materials, while the presence of one or several buried humus horizons is consistent with the synlithogenic soil formation type and the accumulative–sedimentary (sedimentation) pedogenesis model. Based on the data collected in the course of this study, landscape and soil maps of Southern Cisbaikalia have been produced by interpolating the soil sampling points in the Quantum-GIS program with the application of landscape indication methods.

Keywords: soil cover macro-, meso-, and microlevel, paleocryogenic Late Pleistocene microrelief, cryogenic wedge-shaped structures, postlithogenic and synlithogenic soil formation types, denudation and sedimentation pedogenesis models

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INTRODUCTION

The set of soils that constitute the soil cover is a mandatory and essential condition for biodiversity conservation and the stability of geo- and ecosystems. A soil formed as a result of the effects of soil formation factors is a complex, dynamic, self-organizing, and self-developing open-type system that functions by exchanging information, matter, and energy with other systems: the atmosphere, lithosphere, hydrosphere, and biosphere. The development of different soil types is determined by the presence of certain profile-forming processes that proceed at different rates and are clearly manifested in denudation, sedimentation, and other pedogenesis models [1, 2]. The sophistication of the soil cover normally results in the natural growth of biodiversity; while its simplification (e.g. in the course of agropedogenesis) results in a sharp decline of this parameter [3–5]. The most intense land development

is currently observed in the southern part of Eastern Siberia, including Southern Cisbaikalia. Therefore, the assessment of the soil diversity and development features and identification of soil spatial distribution patterns in various landscapes are of key importance both for theoretical and practical purposes.

SUBJECTS AND METHODS

Southern Cisbaikalia with its subtaiga, forest–steppe, steppe, and dry-steppe landscapes was selected as a model area for this study. It occupies the southeastern part of the Central Siberian Plateau on the southern edge of the Siberian Precambrian platform (52°–54° N, 102°–105° E). The wedge-shaped region is known as the Irkutsk Amphitheater [6]. It includes the Irkutsk–Cheremkhovo plain and the southern part of the Cis-Baikal depression representing fore deeps of the Siberian platform, as well as the

Olkhon plateau, a tectonic block between the Baikal ridge and Baikal kettle.

The primary soil formation factor in Southern Cisbaikalia is its sharply continental climate determined by the position of the region in the center of the Asian continent, orographic isolation, and strong influence of the Siberian anticyclone. The subtaiga and forest–steppe areas are affected by humid climate with moderately warm summers and moderately severe winters with little snow; while steppe areas are affected by an insufficiently humid climate with moderately warm summers and moderately severe winters with little snow [6].

The climatic heterogeneity is determined by the relief, which acts as the primary redistributor of heat and moisture. Specific features of local air circulation mechanisms contribute to the formation of vertical zonation, the kettle effect, and arid-shadow zonation. The general orientation of the ridge macroslopes to the west (northwest) and east (southeast) and the prevailing western transfer of air masses strengthen the role of the exposure factor. The differences in precipitation increase the thermal differentiation of slopes: northern slopes exceed southern ones in the amount of received precipitation. Concurrently, the oppositely directed effects of moisture and thermal factors contribute to the formation of different landscapes and soils on the northern and southern slopes [7].

From the geological perspective, Southern Cisbaikalia is a platform with a Precambrian crystalline basement covered by a thick layer of Paleozoic and, in some places, Mesozoic deposits. The Irkutsk–Cheremkhovo plain is constituted by mostly Jurassic sandy–clayey deposits represented by sandstone, aleurolite, argillite, conglomerates, and carbonaceous shale rocks with coal interlayers covered by thick Quaternary deposits. Jurassic rocks are weathering relatively easily, which results in the formation of soft-shaped relief forms and vast river valleys. Lower and Upper Cambrian sandy–marl rocks adjoin the Jurassic deposits from the southwest, southeast and north in the form of a wide strip. Cambrian rocks are especially widespread in the Cis-Sayan region and in the Cis-Baikal depression. In the Olkhon region, basic rocks occur in small contours. Proterozoic deposits are widespread there: sandstone, aleurolite, and various shale, gneiss, and tuff rocks; igneous rocks of the same age include granite, granosyenite, porphyrite, and granodiorite [6, 8].

The main pattern regulating the spatial differentiation of the vegetation cover in Southern Cisbaikalia is its altitudinal (vertical) zonation. A joint manifestation of the kettle effect and foothill (arid-shadow) zonation results in the widespread occurrence of subtaiga cowberry–grassy and forb pine and larch–pine forests within vast depressive morphostructures of the Irkutsk–Cheremkhovo plain and in the southern part of the Cis-Baikal depression. Insular steppes are widespread in the lower tier of the vertical zonation system:

on wide river terraces present on the southern slope of the Lena–Angara plateau [9].

Boreal vegetation predominates in the region; it is widespread south of the south-taiga subzone and forms a piedmont (subtaiga) belt in the East Sayan spectrum of altitudinal belts. Two types of steppe landscapes are present in Southern Cisbaikalia: ancient dry steppes and young meadow–steppes. They are represented by South-Siberian formations of forb–gramineous and gramineous steppes [11] and by dry steppes (Tazheranskaya steppe) in the Olkhon region [8]. Steppe landscapes are widespread only on slopes of river valleys in topographical depressions [10].

The study was performed using the comparative environmental–genetic [12] and substantive–genetic [13] approaches. The soil–geographical surveys were conducted in Southern Cisbaikalia in the period from 2005 to 2018. More than 100 soil profile cuts were established. Soil diagnostics were performed on the basis of their morphological descriptions and properties; the studied soils have been classified and identified in accordance with the principles stipulated in [13].

The soil map of Southern Cisbaikalia was produced in the Quantum-GIS program. The interpolation of the soil sampling points performed using landscape indication methods enabled the transition from key soil plots to soil distribution ranges on the map. Morphometric parameters of the relief determining the redistribution of heat and moisture were used as indicative characteristics. The topographic map made it possible to take into account such parameters as the shape of the land surface (watersheds, slopes with different exposures, height above the local erosion basis, etc.). In addition, space images [14, 15], a scheme of key areas, and field descriptions of the key soil profiles were used. The produced spatial model of soil formation factors was cross-checked against descriptions of the soil profile cuts.

The soil properties were determined using classical and modern methods commonly accepted in soil science and ecology [16]. The elemental composition of the mineral fraction was determined in two ways: (1) spectrographically with DFS-8 and ISP-30 devices at the analytical center of the Sochava Institute of Geography, Siberian Branch, Russian Academy of Sciences (Irkutsk); and (2) using the X-ray fluorescence method with an S4 Pioneer X-ray fluorescence spectrometer (Bruker AXS, Germany) at the Vinogradov Institute of Geochemistry, Siberian Branch, Russian Academy of Sciences (Irkutsk).

Radiocarbon dating of modern and buried humus horizons present in depressions was performed on the basis of carbon present in humic acids at the radiocarbon dating laboratory of the Institute of Geography, Russian Academy of Sciences (Moscow) [17]. The elemental composition of humic acids was determined with an CHNS EA-1112 NEOLAB elemental analyzer

(a)

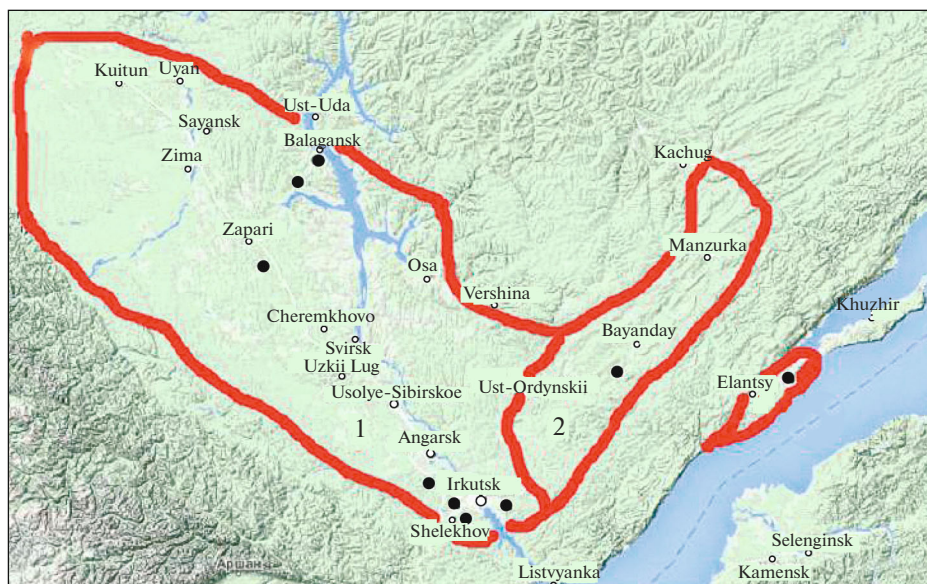


Fig. 1. Survey, landscape, and soil maps of Southern Cisbaikalia. (a) Satellite image (<http://bestmaps.ru/map/google/terrain/7/53.503/104.739>) with observation points, soil profile sections, and sampling points plotted on it. (b) Landscape map of the region. Landscapes: (1) medium- and low-mountain taiga, subtaiga, and south-taiga light-coniferous and in some places dark-coniferous; (2) south-taiga–subtaiga forest–steppe and in some places steppified-insular; (3) piedmont–foothill and smooth-slope steppe and dry-steppe with sparse larch trees; (4) valley–plain hillside steppe and meadow–steppe with meadows, swamps, birch groves, and shrubs. (c) Soil map of the region. (1–15) See Table 1 for the soil nomenclature.

at the Irkutsk Institute of Chemistry, Siberian Branch, Russian Academy of Sciences (Irkutsk).

RESULTS AND DISCUSSION

A unique combination of soil formation factors (i.e., the joint manifestation of the kettle effect, altitudinal (vertical) zonation, and piedmont (arid-shadow) zonation) resulted in the development of sharply contrasting landscapes. Small differences in heat supply even between genetically distant soils are determined by their territorial proximity. A low energy level of the soil formation processes is a distinct feature of the region.

According to the soil zoning of the area occupied by the former USSR [18], the soil cover in the region belongs to a soil district of the subboreal belt; it is the only one located within the boreal belt. According to [19], the soil cover in the region belongs to the piedmont and low-mountain districts, as well as the plain district. The predominant soil types in the plain district are chestnut, petro-, litho-, carbopetro- and carbolithozems, gray-humus, light-humus, and gray soils. Sod–podzolic, gley podzolic, humic-hydromorphic, muck-hydromorphic, eutrophic peat, chernozem, and gray- and dark-humus soils are widespread in the B4 district.

The performed soil–geographical studies made it possible to establish that sod–podzolic soils (AY-EL-BEL-BT-C), podzolized brown forest soils (AYe-BM-C),

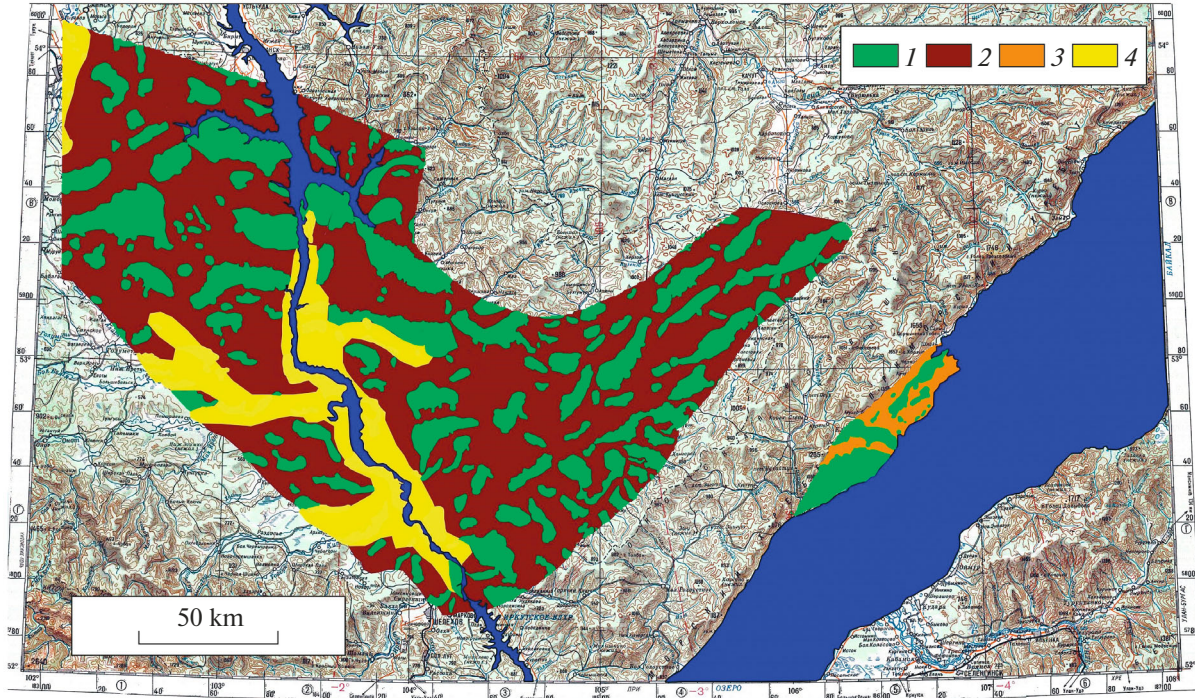
and residual-calcareous brown forest soils (AYca-BMca-Cca) are confined to subtaiga watershed heads. Typical gray soils (AY-AEL-BEL-BT-Cca), metamorphic gray soils (AY-AEL-BM-Cca), and clayey-illuvial chernozem soils (AU-BI-Cca) are formed in the forest–steppe in the middle and lower parts of slopes. On river terraces (steppes and dry steppes), the soil diversity is represented by dispersed-calcareous chernozem soils (AU-BCA-Cca) and chestnut soils (AJ-BMK-CAT-Cca).

Forest–steppe soils occupy 61% of Southern Cisbaikalia; subtaiga soils, 21%; steppe and dry-steppe soils, 3%; and soils of river valleys, 15% (Fig. 1, Table 1).

Soil distribution patterns in Southern Cisbaikalia are determined both by changes in bioclimatic conditions from west to east and by an increase in the height above sea level [22]. Within the mountain taiga range in the southwestern and northeastern parts of Cisbaikalia, combinations of soils with eluvial–illuvial and undifferentiated profiles have been formed. Soils of piedmont taiga landscapes occupy medium and low locations covered by a thin layer of sedimentary rocks. Podzolic and sod–podzolic soils are widespread in the upper part of the taiga belt with loose parent rocks; while (gley) (peat-) podzols and (peat-) podzolized brown soils, in the highest part (over 1200 m). Combinations of sod–podzolic and podzolic soils predominate on acid silicate deposits.

The lithological composition of the parent rocks represented by Lower and Upper Cambrian deposits

(b)



(c)

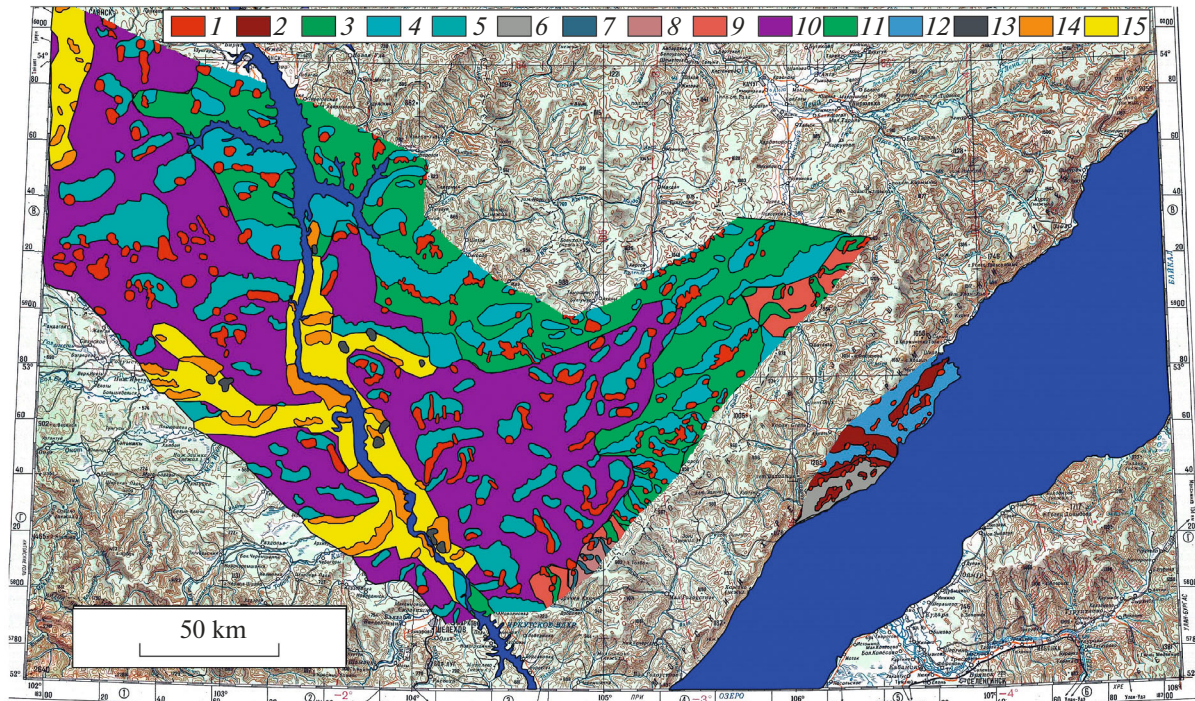


Fig. 1. (Contd.)

contributes to the formation of distinct soils, including residual-calcareous brown forest soils (soddy calcareous soils). A comparison of the landscape and soil maps shows that under the same vegetation type represented by forest and steppe communities, a clear

alteration of soil types in the northeastern direction is observed. This pattern is determined by changes in the composition of soil parent rocks: from Jurassic non-calcareous or low-calcareous to Cambrian high-calcareous ones.

Table 1. The main soil formation factors in Southern Cisbaikalia

Contour no.	Soils	Main soil formation factors					vegetation	% of the total area	Total area
		annual air temperature, °C	annual precipitation, mm	relief	parent rocks, altitude above sea level, m	6			
1	2	3	4	5	6	7	8	9	
1	Sod-podzolic, including residual-calcareous sod-podzolic soils and sod-(peat)-podzols	-2.8	415	Subtaiga soils Watershed	(y,u)PR ₁ , V, R, E, J, 600–1745	Medium- and low-mountain small-grass-green-moss fir-Siberian pine forests, subtaiga dwarf Arctic birch-wild rosemary and mountain-basin larch forests, south-taiga dwarf-shrub (cowberry)-grassy (green-moss) pine and larch-pine forests	2.4	20.6	
2	Peat-podzolic, including residual-calcareous and gleyic ones, peat-podzols, and peat-podzolic brown soils			Slope with exposure to the north	(y,u)PR ₁ , R, 600–1250	Low- and medium-mountain shrub-grassy (green-moss) pine and larch-pine forests with fragments of native dark-coniferous stands	1.3		
3	Sod-podzolic, sod-podzolic brown, and residual-calcareous sod-podzolic soils				V, 600–1000	Subtaiga, mountain-basin, and low-mountain shrub-grassy pine and larch-pine forests steppified in some places	0.8		
4	Coarse-humus podzolic, sod-podzolic, and residual-calcareous brown forest soils	-3.2	383		E, 700–1000	Subtaiga and in some places low-mountain cowberry-grassy and grassy pine and larch-pine forests, sometimes steppified	8		
5	Peat-podzolic brown and sod-podzolic soils				J, 600–800	Subtaiga cowberry-grassy pine and larch-pine forests	7.8		

Table 1. (Contd.)

Contour no.	Soils	Main soil formation factors						% of the total area	Total area
		annual air temperature, °C	annual precipitation, mm	relief	parent rocks, altitude above sea level, m	vegetation			
1		3	4	5	6	7	8	9	
6	Coarse-humus brown forest and podzolized brown forest soils	-2.4	486	Slope with exposure to the south	yPR ₁ , 700–1000	South-taiga and low-mountain cowberry-grassy pine and larch-pine forests and in some places shrub-green-moss Siberian pine forests	0.3		
7	Gray, sod-brown-podzolic, and sod-podzolic soils	-2.1	434	Forest-steppe Slope with exposure to the north	R, 700–1000	Forest-steppe combinations of forb pine-birch and birch-aspen forests with fragments of gramineous-forb steppes	1.1	61.2	
8	Gray metamorphic, dark gray, and dark-humus residual-calcareous soils	-1.1	489	Slope with exposure to the south	R, 700–1000	Forest-steppe forb pine-birch forests	1.8		
9	Dark gray metamorphic and dark-humus residual-calcareous soils	-2.7	380		V, 600–1000	Forest-steppe and in some places mountain-forest-steppe forb pine-birch and birch-aspen forests with fragments of gramineous-forb and shrub steppes	3.1		
10	Dark-humus soils and clayey-illuvial (hydrometamorphized) chernozems				J, 600–800	Forest-steppe forb pine-birch forests, forb gramineous steppes, and steppified meadows	32.9		
11	Dark gray, gray, and dark-humus residual-calcareous soils				E, 700–1000	Meadow feathergrass-forb and gramineous-wormwood steppes with fragments of pine-birch forests	22.3		

Table 1. (Contd.)

Contour no.	Soils	Main soil formation factors					vegetation	% of the total area	Total area
		annual air temperature, °C	annual precipitation, mm	relief	parent rocks, altitude above sea level, m	6			
1	2	3	4	5	6	7	8	9	
		Soils of steppes, dry steppes, and river valleys							
12	Gray-humus, chestnut, and chestnut-like soils	-4.1	260	Ravine—ridge relief with exposure to the north-east	PR ₁ , 800—1250	Low- and medium-mountain steppified larch—pine forests with fragments of bunchgrass—gramineous steppes	3.4	3.4	
13	Peat—mineral and peat—gleyic alluvial soils and muck—gleyic and dark-humus (gleyic) alluvial soils	-3.6	395	Flattened surfaces within river valleys (low floodplains)	Q, <500	Waterlogged and dwarf-shrub meadows and shrub—moss floodplain forests	0.9	14.8	
14	Humic stratified-alluvial soils and peat—gleyic and muck—gleyic alluvial soils			Smooth slopes with exposure to the north within river valleys (high floodplains and terraces)	Q, 500—700	Mixed floodplain forests and forb—gramineous meadows, sometimes waterlogged	3.1		
15	Humic alluvial, dark-humus metamorphized, muck—dark-humus soils, and dispersed-calcareous chernozems			Smooth slopes with exposure to the south within river valleys (high floodplains and terraces)	Q, 500—700	Grass—shrub light-coniferous and birch forests and steppified meadows	10.8		

Rock nomenclature: (PR₁) Lower Proterozoic (gneiss, marble, quartzite, amphibolite, ferruginous quartzite, dolomite, effusive, sandstone, and shale rocks); (yPR₁) Lower Proterozoic (granite, granodiorite, granosyenite, pegmatite, granite—porphyre, and gneiss—granite rocks); (uPR₁) Lower Proterozoic (diabase, gabbro-diabase, and gabbro-diorite rocks); (R) Riphean (shale, sandstone, conglomerates, limestone, dolomite, marl, quartzite, and gneiss rocks); (V) Vendian (limestone, dolomite, aleurolite, sandstone, argillite, marl, and conglomerates) (E) Cambrian (sandstone, aleurolite, argillite, limestone, conglomerates, cupreous sandstone, gypsum, and rock salts); (J) Jurassic (sandstone, aleurolite, conglomerates, coal, breccia, and kaolinite rocks); (Q) Holocene quaternary deposits (pebble, sand, loam, silt, and other alluvial—deluvial deposits).

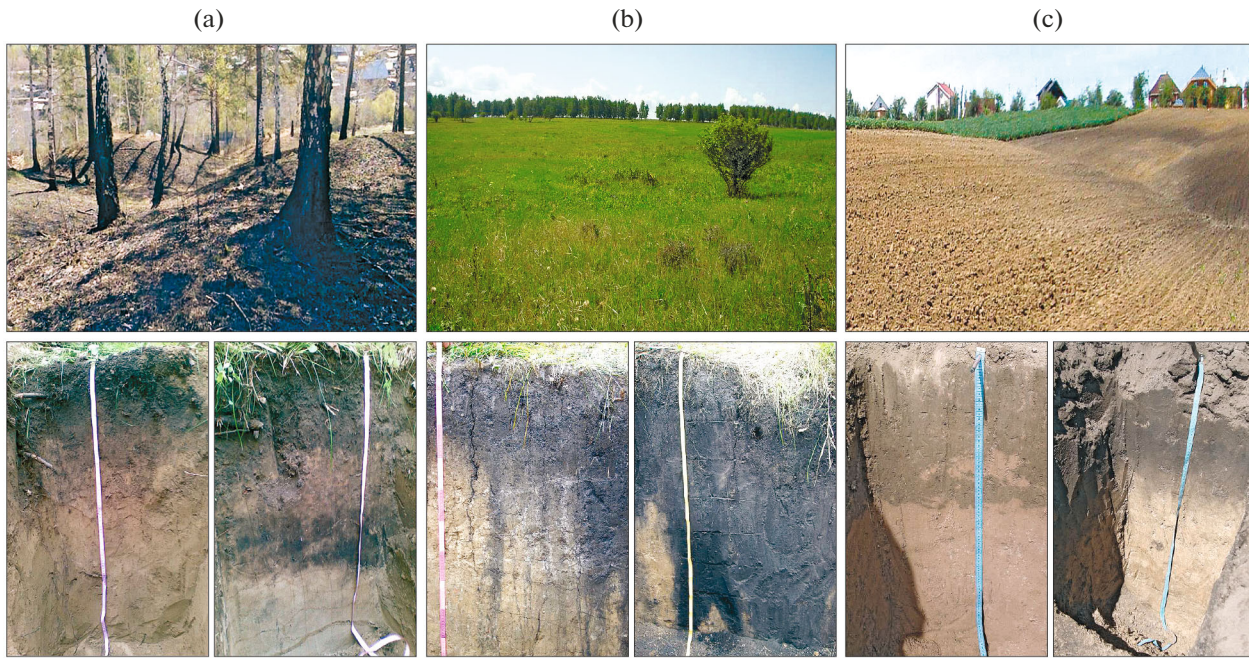


Fig. 2. Manifestations of the hummocky–pitted relief in Southern Cisbaikalia: (a) forest (soil profile cuts established on a hummock and in a depression), (b) steppe (soil profile cuts established on a hummock and in a depression), and (c) arable land (soil profile cuts established on a hummock and in a depression).

At the mesolevel, the spatial distribution of soils is significantly affected by the slope exposure. Windward northwestern slopes that receive a greater amount of precipitation are occupied by sod–podzolic, sod–brown–podzolic, typical gray, and clay–illuvial chernozem soils. On leeward less moistened southeastern slopes, podzolized brown forest soils, gray metamorphic soils, dispersed–calcareous chernozem, and chestnut soils are widespread.

Paleocryogenesis has significantly affected the diversity of soils, as well as their structure, properties, and spatial distribution patterns [23]. The phenomenon is manifested in the polygonal–block and hummocky–pitted microrelief formed in the end of the Pleistocene epoch (Sartan period) distinguished by a significant aridization of the climate amid a strong cooling. The periglacial conditions contributed to the initial division of the surface into polygons and cracks filled with wedge ice that has completely melted in the Holocene. The remaining cavities (cracks–depressions) were filled in the forest zone with low-humic materials of the walls of the collapsing cracks; in the steppe, with materials rich in humus from the upper horizons of high-humic soils of the polygons–hummocks. These hummocks represent polygons (blocks) with undisturbed structure up to 3.5 m high and 10–20 m in diameter (Fig. 2).

Soils formed on the polygons (blocks) are auto-morphic and autonomous; they represent various “zonal” types depending on the landscape. As a result of erosion and deflation, the soil material (usually

finely dispersed humic one) is drifted away from the polygon’s surface and accumulates in cracks–depressions, which is consistent with the denudation pedogenesis model.

Soils formed in cracks–depressions are semihydro-morphic and heteronomous; they are located in the immediate vicinity (10 to 40 m) to the soils of hummocks. Soils in depressions sharply differ by their genesis, evolution, and properties from the soils of polygons–hummocks; they are conjugated with the soils of hummocks genetically and geochemically, and their formation is consistent with the accumulative–sedimentary (sedimentation) pedogenesis model. Therefore, in accordance with [13], the majority of soils present in cracks–depressions have been subsumed under the trunk of synlithogenic soils and the division and type of dark-humus stratozems (AU-RU-D), gray-humus stratozems (AY-RY-[ABC]) and dark-humus (AU-RU-[A-B-A-C]) stratozems on buried soils. A part of their profile is represented by a stratified humic layer of gray-, dark-, or light-humus horizons more than 40-cm thick buried under some other soil or a mineral substrate.

The differentiation of soil formation processes at the soil cover microlevel (i.e., blocks (hummocks) and depressions between them (pits)) is manifested in the form of polychronous regular-cyclic fissure complexes [24] (Fig. 3). The analysis of the soil properties shows that they are inconsistent with the modern vegetation cover because soils and vegetation evolve at different rates. As a result of the climate

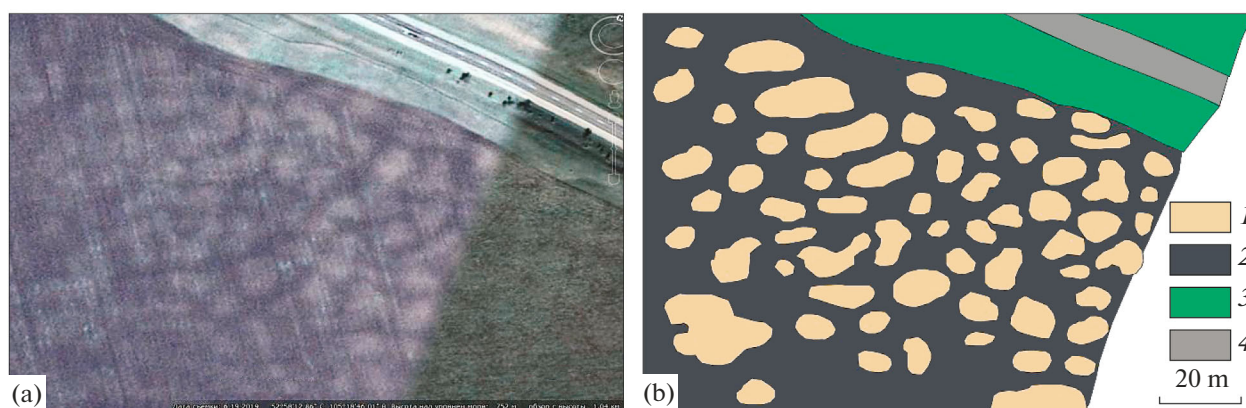


Fig. 3. Soils of virgin, plowed, and fallow lands (10 km to the east of the village of Ol'zony, Bayanday district). (a) Google Earth satellite image (52.58° N, 105.18° E; altitude above sea level: 752 m; view from a height of 1.04 km). (b) Soils: (1) on hummocks (dark clayey-illuvial agrozeims); (2) in depressions (dark-humus agrostratozeims and dark-humus agrostratozeims on buried soils); (3) on steppified sections of the roadside belt (clayey-illuvial chernozems on hummocks and dark-humus agrostratozeims and dark-humus agrostratozeims on buried soils in depressions) and on fallow lands (clayey-illuvial postagrogenic agrochernozems on hummocks and dark-humus postagrogenic agrostratozeims in depressions); and (4) under the road.

warming and its fluctuations in the Holocene, the area occupied by forest and steppe landscapes has changed [25], which is reflected in the current state and complexity of the soil cover, as well as the soil structure and properties (Table 2).

The conservative properties (i.e., the elementary and granulometric composition of the mineral fraction) reflect the past soil development stages and are consistent with the former vegetation whose influence could result in the formation of sod–podzolic, podzolized brown forest, and gray soils whose profile is differentiated according to the podzolic type.

The aridity and severity of the climate, as well as the primary composition of soil parent rocks, determine the weak manifestation and low rates of such processes as weathering, soil formation, and podzolization in the studied subtaiga and forest–steppe soils; this is the cause of the low acidity levels in the upper horizons and noticeable alkalization in the lower ones. The soil weathering index (i.e., the ratio between silicate and nonsilicate iron, Fe_s/Fe_{ns}) [26] confirms the low rates of weathering and soil formation processes: the lower is the index value, the stronger weathering processes are manifested.

Long periods of freezing significantly affect the soil formation. Cryogenesis reduces the chemical flow and solubility of many elements and enriches them with highly or poorly soluble salts. This is the cause of the slightly acid, neutral, or slightly alkaline soil reaction, elevated content of humus and exchangeable bases, low rates of weathering and soil formation processes, reduction of the soil biological activity, and slowing down of organic matter decomposition processes.

Similar to forest landscapes, in steppe soils, significant amounts of humus and exchangeable bases are

concentrated in a rather thin (0–50 cm) humus horizon (Table 3).

The high content of roots in the upper part of the profile and its sharp reduction with depth due to low temperatures at the bottom of the profile reflect the regional specificity of the studied soils. The elevated magnesium concentration is determined by the mineralogical and chemical composition of parent rocks in the region.

In cryogenic wedge-shaped structures, most soil profiles include buried humus horizons (Table 4).

In forest soils, a lighter horizon occurs between the modern and buried humus horizons; while in the steppe, the color intensity increases down the profile. Radiocarbon dating, the humus properties, and the elemental composition of humic acids indicate that the daylight humus horizons formed in the modern soil formation phase; while the buried ones formed during the warmer Atlantic time, as distinguished by the development of tall-grass mesophilic vegetation and high-humic soils [27].

It has been established that the soil cover formation is regulated in general by a certain genetic code that is determined in the course of the evolution of the natural environment. The paleogeographic conditions that determine the soil diversity, spatial distribution, and specificity of soil formation processes are a type of foundation (matrix).

CONCLUSIONS

(1) One distinct feature of soil formation processes in the study area is a significant lag between changes in the bioclimatic conditions and subsequent changes in soil properties. The profiles of most regional soil types that occupy elevated relief elements, from the macro-

Table 2. The chemical, physical, and physicochemical properties of some soils formed on hummocky polygons (subtaiga and forest-steppe)

Soil	Horizon, depth (cm)	pH H ₂ O	Humus, %	Ca ²⁺	Mg ²⁺	H ⁺	Na ⁺	CaCO ₃ , %	$\frac{\text{SiO}_2}{\text{Al}_2\text{O}_3}$	Fe _s /Fe _{ns}	Granulometric composition (%)	
											<0.001 mm	<0.01 mm
1	2	3	4	5	6	7	8	9	10	11	12	13
Soils of hummocky polygons in subtaiga												
Sod-podzolic	AY 0–5	5.9	4.40	31.0	8.2	26.7	–	–	6.71	2.92	24	44
	EL 5–15	6.3	1.00	20.2	5.0	14.8	–	–	5.88	2.17	20	41
	BEL15–54	6.5	0.50	19.3	7.7	7.1	–	–	6.50	2.43	30	48
	BT 54–75	6.9	0.29	21.6	9.2	5.6	–	–	6.44	4.16	35	55
	C 75–100	6.7	0.10	13.4	8.9	3.6	–	–	7.37	5.53	10	31
Podzolized brown forest soil	AYe 0–15	6.5	10.1	28.3	6.1	8.0	–	–	8.07	3.35	17	35
	BM 15–94	6.4	0.74	17.8	6.4	5.2	–	–	6.81	4.26	23	45
	C 94–120	6.4	0.55	20.5	7.4	3.3	–	–	6.00	4.26	30	54
Typical residual-calcareous brown forest soil	AYca 0–38	7.9	4.59	19.3	3.1	–	1.1	4.0	7.92	2.19	19	36
	BMca 38–77	8.5	0.72	12.4	5.9	–	1.3	18.0	7.46	2.59	17	33
	Cca77–130	8.2	0.66	8.5	8.6	–	1.6	12.0	7.69	2.50	19	32
Soils of hummocky polygons in forest-steppe												
Typical gray soil	AY 0–20	6.5	3.7	10.9	5.2	5.2	–	0	8.21	3.29	10	21
	AEL 20–30	6.5	0.74	9.5	3.0	2.1	–	0	8.29	1.28	12	20
	BEL 30–50	6.2	0.21	7.3	3.7	1.7	–	0	9.23	1.65	11	14
	BT 50–70	6.5	0.12	3.1	2.4	1.2	–	0	8.21	5.03	17	21
	Cca 70–115	8.2	0.22	2.5	3.2	–	–	1.5	5.44	5.04	6	10
Metamorphic gray soil	AY 0–16	6.4	3.90	34.0	4.6	5.9	–	0	7.47	1.56	11	24
	AEL 16–30	6.0	3.30	17.6	8.2	1.9	–	0	7.33	2.29	12	24
	BM 30–78	6.7	0.38	18.3	12.4	1.2	–	0	6.50	2.11	12	24
	Cca 78–130	8.6	0.21	24.5	13.2	–	–	5.0	6.53	2.48	12	31
Clayey-illuvial chernozem	AU 0–40	6.2	4.64	28.3	5.4	–	–	0	6.33	9.00	20	43
	BI 40–75	6.5	0.91	22.1	6.6	–	–	0	6.33	11.5	25	45
	Cca 75–120	7.9	0.62	24.9	11.0	–	–	1.0	6.28	10.1	21	42
Soils of cryogenic wedge-shaped structures (depressions) in forest-steppe												
Gray-humus stratozem on buried soil	AY 0–15	6.0	4.40	13.5	5.8	12.5	–	–	5.70	1.50	15	29
	RY 0–37	5.9	2.33	14.5	4.5	10.6	–	–	5.78	1.50	14	28
	[A] 37–70	5.8	5.53	15.1	3.7	8.6	–	–	6.93	1.56	14	33
	[B] 70–90	5.8	0.49	11.1	3.2	8.1	–	–	6.81	1.56	15	38
	[C] 90–125	5.8	0.48	10.6	3.8	6.0	–	–	6.67	1.86	9	19

(–) parameter was not measured (also applies to Table 3).

Table 3. The chemical, physical, and physicochemical properties of some soils formed on hummocky polygons and in cryogenic wedge-shaped structures (depressions) (steppe and dry steppe)

Soil	Horizon, depth, cm	pH H ₂ O	Humus, %	Ca ²⁺	Mg ²⁺	H ⁺	Na ⁺	CaCO ₃ , %	SiO ₂ / Al ₂ O ₃	Fe _s / Fe _{ns}	Granulometric composition, %	
				(mg-equiv/100 g of soil)					<0.001 mm	<0.01 mm		
Soils of hummocky polygons in steppes and dry steppes												
Dispersed-calcareous chernozem	AU 0–49	8.1	4.34	20.3	7.6	–	0.60	0.4	7.64	5.67	16	32
	BCA 49–122	9.0	1.24	9.4	12.1	–	1.64	8.0	7.64	6.69	21	37
	Cca 122–130	9.6	0.59	0.0	18.0	–	3.48	24.0	7.58	9.00	21	29
Typical chestnut soil	AJ 0–20	7.9	3.83	8.3	0.0	–	0.46	0.1	8.77	7.33	10	15
	BMK 20–50	8.5	1.95	4.6	3.0	–	0.84	3.0	6.76	6.14	14	21
	CAT 84–124	8.4	0.19	5.3	5.0	–	1.83	3.9	6.70	11.5	14	18
	Cca 124–150	8.6	0.21	3.4	3.9	–	1.60	3.4	6.83	13.3	12	17
Soils of cryogenic wedge-shaped structures (depressions) in steppes												
Dark-humus stratozem	AU 0–30	5.4	7.41	30.4	6.2	–	–	0	6.33	9.00	24	43
	RU 30–120	5.5	7.52	31.3	11.7	–	–	0	6.33	11.50	29	45
	D 120–130	5.6	9.71	27.0	10.4	–	–	0	6.28	10.11	28	44

Table 4. Radiocarbon dating of humic acids present in modern and buried humus horizons in cryogenic wedge-shaped depressed structures (stratozems [27])

Soil	Laboratory no.	Horizon, depth, cm	Radiocarbon age, ¹⁴ C years ago	Calibrated age range, years ago
Gray-humus stratozem on buried soil	IGAN-3214	A(RY) 0–37	1960 ± 50	1867 BP–1952 BP 1959 BP–1972 BP 1977 BP–1986 BP
	IGAN-3215	A(A) 37–70	4260 ± 60	4650 BP–4671 BP 4701 BP–4759 BP 4944 BP–4948 BP
Dark-humus stratozem	IGAN-3219	Ad(AU) 0–30	2510 ± 40	2497 BP–2597 BP 2612 BP–2638 BP 2687 BP–2720 BP
	IGAN-3217	A(AU) 13–30	2720 ± 50	2768 BP–2854 BP
	IGAN-3220	A(RU) 30–68	6030 ± 70	6759 BP–2597 BP 6784 BP–6966 BP

to microlevel, have been formed as a result of overlaying of different horizons and their subsequent transformation or conservation.

(2) At the macrolevel, the joint influence of the kettle effect and the foothill (arid-shadow) form of vertical zonation contributed to the development of sharply contrasting landscapes in Southern Cisbaikalia. Watershed heads are occupied by subtaiga; middle and lower parts of slopes, by forest–steppes; while river terraces, by steppes and dry steppes. Low moisture and heat supply levels determine the territorial proximity of soils with sharply different structures and properties.

(3) The regional soil cover is constituted by soils belonging to the texture-differentiated (sod–podzolic, podzolized brown forest, and typical gray soils), structural-metamorphic (residual-calcareous brown forest soils and gray metamorphic soils), humus-accumulative (clayey-illuvial and dispersed-calcareous chernozems), and carbonate-accumulative (chestnut soils) divisions of the postlithogenic trunk.

(4) At the mesolevel, the spatial distribution of soils is significantly affected by the slope exposure: windward northwestern slopes are occupied by sod–podzolic, sod–brown–podzolic, typical gray, and clay-illuvial chernozem soils; while leeward south-

eastern slopes are occupied by podzolized brown forest soils, gray metamorphic soils, dispersed-calcareous chernozems, and chestnut soils.

(5) The hummocky–pitted paleocryogenic microrelief determines the soil cover microlevel, which consists of contrasting soil microcombinations. Normally, it is represented by complexes of automorphic autonomous soils on hummocky polygons and by semihydromorphic heteronomous accumulative soils in cryogenic wedge-shaped structures (depressions). As a result, the degree of sophistication of the soil cover significantly increases and the soil diversity increases.

(6) On hummocky polygons, soils are formed in undisturbed ground masses, which is consistent with the postlithogenic soil formation type. As a result of erosion and deflation, soil is continuously drifted away and accumulates in depressions, which is consistent with the denudation pedogenesis model.

(7) Cryogenic wedge-shaped structures confined to depressions are formed in redeposited soil materials that drifted from adjacent hummocky polygons, which indicates the synlithogenic soil formation type. The presence of one or several buried humus horizons that sharply differ from the modern (daylight) humus horizons by their properties reflects the accumulative–sedimentary (sedimentation) pedogenesis model.

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COMPLIANCE WITH ETHICAL STANDARDS

Conflict of Interest

The authors declare that they have no conflict of interest.

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