Soils of mountain-forest landscapes of the Zeysky Nature Reserve

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Abstract. The article describes the properties and modern classification position of mountain-forest soils at the eastern end of the Tukuringra Range. Based on morphological analysis, three groups of soils have been identified within the study area: Cambisols, Gleysols and Podzols. The soils of the Cambisols group are associated with the slopes of the southern exposure and are characterized by the presence of humus horizon, good drainage, expressed rockiness, and formation of an aggregated metamorphosed layer of brown colour in the middle part of the profile. Soils of the Gleysols group are formed in permafrost areas within the lower part of the western exposure slopes. The lower part of the soil profile is characterized by intense thixotropy. The northern exposure slopes are characterized by high prevalence of permafrost, thin rank soils, and bedrock exposures. Under these conditions, soils of the Podzols group are described within the smooth slopes and floodplain terraces of mountain rivers. These soils are formed on colluvial deposits; they have light granulometric composition and good drainage. In the upper part of the profile, the dry peaty layer is well developed as a result of conservation of organic residues.

1. Introduction
Current knowledge of the properties, genesis and geography of mountain soils in the Amur region remains fragmented and poorly reflected in scientific literature on the region. The remoteness from major research centers and inaccessibility of the mountainous areas in the Zeya River valley constitute obstacles to full-scale soil research works.

Due to the soil function of ensuring the species and population diversity of flora and fauna, along with being the special environment for evolution of living organisms, the study of mountain soils in nature reserves can serve as the basis for organization of conservation activities aiming at preservation and restoration the typical biogeocenoses, as well as rare and unique natural ecosystems. Soils in nature reserves, as the least exposed to anthropogenic impact, can serve as soil standards [1], becoming objects of monitoring and indicators of sustainability of natural ecosystems.

Studies of mountain soils in the region began in 1908–1909, during expeditions of the Resettlement Department of the Russian Empire. In the second half of the twentieth century, comprehensive studies were carried out, which revealed new properties and diagnostic features of mountain-forest soils and specified geographical patterns of their distribution. Based on these data, the Legend of the World Soil
Map [2], which served as the basis for the World Reference Base for Soil Resources [3], assigned mountain soils of the region to the Cambisols group. However, research in recent decades [4–9] also demonstrates a wide distribution of soils from other reference groups.

The relevance of the study undertaken results from the need to address the genesis and classification of mountain-forest soils in the Amur Region in accordance with the principles of the World Reference Base for Soil Resources (WRB), as well as to establish a network of soil and environmental monitoring sites based on the collection of soil monoliths sampled during the expedition and stored at the Central Soil Museum (St. Petersburg, Russia).

The aim of the work was to study the soils formed in the mountain-forest landscapes of the Zeysky Nature Reserve and to conduct their comparative analysis. In the course of the study the following tasks were carried out: study of soils’ morphological structure, analysis of soils’ chemical, physical, physical-chemical properties, and definition of their modern classification position.

2. Materials and methods
Field studies were carried out in the summer of 2019 in the mountain-forest areas of the Zeysky Nature Reserve. The territory of the reserve covers the eastern end of the Tukuringra Range with absolute heights from 600 to 1600 m, which is composed mainly of metamorphic slates, sandstones, quartzites, crystalline limestone gneisses, and marbles scoured by magmatic rocks [10].

The main survey areas were identified on the basis of the Reserve’s vegetation map [11] and satellite images; they included the most common types of plant communities within the Reserve, within which five reference soil profiles were excavation:

1. Cambisol (Soil profile 1–2019) N 53° 51’ 19.9” E 127° 21’ 37.7”; height above sea level is 392 m.
   Vegetation: Quercus mongolica Fisch. ex Ledeb., Betula dahurica Pall., Lespedeza bicolor Turcz., Carex supermascula V.I.Krecz., C. lanceolata Boott.

2. Cambisol (Soil profile 2–2019) N 53° 51’ 41.4” E 127° 21’ 33.3”; height above sea level is 600 m.
   Vegetation: Larix gmelinii (Rupr.) Kuzen., Vaccinium vitis-idaea L.

3. Gleysol (gelic) (Soil profile 3–2019) N 54° 05’ 13.9” E 126° 52’ 29.5”; height above sea level is 614 m.
   Vegetation: Betula platyphylla Sukaczev, Larix gmelinii, Vaccinium vitis-idaea, Calamagrostis purpurea (Trin.) Trin.

4. Folic Podzol (Soil profile 4–2019) N 54° 13’ 22” E 126° 55’ 03”; height above sea level is 398 m.
   Vegetation: Larix gmelinii, Betula lanata (Regel) V. N. Vassil., Picea ajanenses Fisch. ex Carriere, Diplazium sibiricum (Turcz. ex Kunze) Sa.Kurata, Aruncus dioicus (Walter) Fernald, Filipendula palmata Maxim.

5. Histic Entic Podzol (Soil profile 5–2019) N 54° 13’ 31.1” E 126° 56’ 03.9”; height above sea level is 328 m.
   Vegetation: Picea ajanenses, Swida alba (L.) Opiz, Diplazium sibiricum, Dryopteris expansa (C.Presl) Fraser-Jenk. & Jermy.

In the soils studied, 22 samples were taken from genetic horizons. Detailed photographing of soils, landscapes and soil covers was carried out, as well as macro photographing of soil horizons. Soil monoliths were selected to be included in the collection of the Central Soil Museum (St. Petersburg, Russia).

Physical (particle size distribution), physic-chemical (various acidity types, total absorbed bases, degree of soil base saturation), and chemical (carbon content of organic compounds, group composition of iron and aluminum compounds using the Tamm and Bascombe methods) indicators were determined using the methods generally accepted in soil science [12–14]. Determination of the group composition (oxalate soluble “amorphous” and associated with organic matter) of iron and aluminum compounds was carried out using the equipment of the Chemical Analysis and Materials Research Centre of the St. Petersburg State University Science Park (Project № 108–10181) and atomic absorption spectrophotometer AA 7000 (Shimadzu, Japan) of the Department of Soil Science and Soil Ecology of the St. Petersburg State University. The names of soil types are given in accordance with the WRB.
3. Result and discussion

3.1. Cambisols
Cambisols soils (figure 1) are typical for all slopes of the southern end of the Tukuringra Range. The main diagnostic feature of these soils is the brown middle horizon with a well-expressed nutty or crumby structure. The brown shades are due to the presence of colouring iron compounds.

In the lower reaches of the Gilyuy River and within the reservoir bed of the Zeya Dam, brown colour can be seen on almost all slopes of the southern exposure and outcrops (in their upper parts). This indicates that soils from the Cambisol group are prevalent. Two soil profiles have been established to study the soils of this group. The first soil type is described on a steep southern slope under the oak and black-birch forest (Soil profile 1–2019). The second soil type is confined to the top of the hill under the larch forest (Soil profile 2–2019).

![Figure 1. Soils of mountain-forest landscapes of the Zaysky Nature Reserve: 1, 2. Cambisols (1–2019 and 2–2019), 3. Follic Podzol (4–2019), 4. Histtic Entic Podzol (5–2019).](image)

Both studied soils are formed on shale rocks within the southern exposure slopes, and are characterized by good drainage, expressed rockiness and absence of distinct permafrost and gleization. The humus horizon is clearly identified in the soils described. In the middle part of the profile, the processes of metamorphization of mineral matter (argillization, structure formation and brunification) have been observed. A description of the soils studied and analytical data are provided below.

Soil profile 1–2019 is characterized by a close to neutral pH level (table 1). The soil has an average cationic exchange capacity (CEC). The degree of soil base saturation (V) is 79% in the humus horizon, 57–60% in the middle part of the soil profile and it further decreases to very low values in the soil–forming rock.

Data from the oxalate extract analysis indicates an undifferentiated distribution of amorphous aluminum in the soil profile. Amorphous iron (Fe$_{am}$) has an accumulative-eluvial-illuvial distribution along the soil profile, with maximum content in the humus horizon and soil–forming rock. The content of aluminum and iron compounds associated with organic matter (Al$_{py}$; Fe$_{py}$) is very low due to the slope position of the described soil and the washout of these compounds outside the soil profile.
The distribution of physical clay and silt fractions over the profile is similar to that of amorphous iron (table 2). The formation of the peak accumulation of all three indicators in the soil-forming rock is associated with development of a seasonal frost layer during winter, which acts as a barrier.

Table 1. Physico-chemical and chemical properties of the soils.

| Depth, cm | C<sub>org</sub>, % | pH | CEC, mmol kg<sup>-1</sup> | Exchangeable cations, mmol kg<sup>-1</sup> | V, % | Tamm’s extract, % | Pyrophosphate extract, % | Remark |
|-----------|-------------------|-----|--------------------------|---------------------------------|------|-------------------|--------------------------|--------|
|           |                   |     | H<sub>2</sub>O | KCl | Ca<sup>2+</sup>+Mg<sup>2+</sup> | Al<sub>ox</sub> | Fe<sub>ox</sub> | Al<sub>py</sub> | Fe<sub>py</sub> |         |
| 1–2019 Cambisol |
| 0–10     | 2.3               | 6.0 | 5.0 | 27.9 | 22.0 | 79 | 0.28 | 0.74 | 0.04 | 0.04 | Humus horizon |
| 15–25    | 1.4               | 5.6 | 4.0 | 23.3 | 13.2 | 57 | 0.30 | 0.66 | 0.05 | 0.03 |
| 30–40    | 0.6               | 5.7 | 3.9 | 20.1 | 12.0 | 60 | 0.27 | 0.54 | 0.04 | 0.02 |
| 50–65    | 0.4               | 5.3 | 3.7 | 19.8 | 4.4  | 22 | 0.32 | 0.64 | 0.07 | 0.02 |
| 2–2019 Cambisol |
| 0–10     | 6.82              | 5.1 | 4.0 | 34.2 | 15.4 | 38 | 0.60 | 1.28 | 0.22 | 0.23 | Humus horizon |
| 15–20    | 2.3               | 4.9 | 3.7 | 30.5 | 4.0  | 13 | 0.68 | 1.35 | 0.24 | 0.25 |
| 20–34    | 1.4               | 4.8 | 3.8 | 32.7 | 6.4  | 20 | 0.84 | 1.33 | 0.25 | 0.21 |
| 34–50    | 0.4               | 5.0 | 4.1 | 21.5 | 3.6  | 17 | 0.91 | 1.22 | 0.27 | 0.15 |
| 3–2019 Gleysol (Gelic) |
| 0–15     | 71.0<sup>a</sup>  | 4.3 | 3.7 | –    | –    | – | – | – | – | – | Peat |
| 20–30    | 1.7               | 4.0 | 3.4 | 35.9 | 18.0 | 50 | 0.51 | 1.72 | 0.15 | 0.25 | Gley layer |
| 30–40    | 1.3               | 4.2 | 3.5 | 36.1 | 15.8 | 44 | 0.47 | 1.12 | 0.15 | 0.15 |
| 52–60    | 1.1               | 4.4 | 3.9 | 40.5 | 13.4 | 33 | 0.83 | 2.49 | 0.24 | 0.33 | Cryometamorphic layer |
| 60–70    | 0.7               | 4.8 | 4.3 | 26.1 | 16.4 | 63 | 0.35 | 0.75 | 0.08 | 0.04 |
| 4–2019 Folic Podzol |
| 0–25     | 54.3<sup>a</sup>  | 4.4 | 3.6 | 42.9 | 19.6 | 46 | 0.13 | 0.26 | 0.04 | 0.09 | Dry peat |
| 25–29    | 1.3               | 4.4 | 3.3 | 29.9 | 18.8 | 63 | 0.20 | 0.43 | 0.03 | 0.05 |
| 29–33    | 1.6               | 4.2 | 3.2 | 45.7 | 16.6 | 36 | 0.67 | 1.20 | 0.06 | 0.15 |
| 35–40    | 0.9               | 4.6 | 3.6 | 21.8 | 12.0 | 55 | 0.18 | 0.42 | 0.02 | 0.04 |
| >60      | 0.3               | 4.5 | 3.4 | 21.5 | 12.2 | 57 | 0.18 | 0.36 | 0.02 | 0.04 |
| 5–2019 Histic Entic Podzol |
| 0–10     | 6.82              | 5.1 | 4.0 | 34.2 | 15.4 | 38 | 0.38 | 0.80 | 0.12 | 0.30 | Dry peat + mineral layer |
| 15–20    | 2.3               | 4.9 | 3.7 | 30.5 | 4.0  | 13 | 0.42 | 0.81 | 0.13 | 0.27 |
| 20–34    | 1.4               | 4.8 | 3.8 | 32.7 | 6.4  | 20 | 0.58 | 1.13 | 0.14 | 0.29 |
| 34–50    | 0.4               | 5.0 | 4.1 | 21.5 | 3.6  | 17 | 0.25 | 0.52 | 0.06 | 0.09 |

<sup>a</sup>Losses of ignition.

Soil profile 2–2019 is characterized by acidic pH level throughout the soil profile. The upper and middle parts of the profile have a high absorption capacity, which drops to average values at the rock level. There is a very low degree of soil base saturation. The carbon content of organic compounds (C<sub>org</sub>) is accumulated over the soil profile. In the humus horizon, C<sub>org</sub> content is 6.82%.
Table 2. Particle size distribution fine earth, fraction content with diameter, mm, in % of weight of soil dried at 105 °C.

| Depth, cm | Fraction content with diameter, mm, in % | Remark |
|-----------|----------------------------------------|--------|
|           | 1−0.25 | 0.25−0.05 | 0.05−0.01 | 0.01−0.005 | 0.005−0.001 | <0.001 | <0.01 |
| 1−2019 Cambisol | | | | | | | |
| 0−10 | 8.9 | 20.1 | 32.0 | 14.2 | 13.8 | 11.0 | 39.0 |
| 15−25 | 14.5 | 29.9 | 22.8 | 10 | 9.5 | 13.3 | 32.8 |
| 30−40 | 18.9 | 32.0 | 20.5 | 8.9 | 10.3 | 9.4 | 28.6 |
| 50−65 | 12.8 | 33.7 | 19.1 | 10.0 | 11.5 | 12.9 | 34.4 |
| 2−2019 Cambisol | | | | | | | |
| 0−10 | 0 | 18.2 | 22.9 | 17.1 | 18.3 | 23.5 | 58.9 |
| 15−20 | 2.0 | 16.1 | 27.3 | 15.5 | 16.9 | 22.2 | 54.6 |
| 20−34 | 4.7 | 18.8 | 26.8 | 14.8 | 16.1 | 18.8 | 49.7 |
| 34−50 | 10.1 | 17.9 | 18.0 | 12.3 | 21.2 | 20.5 | 54.0 |
| 3−2019 Gleysol (Gelic) | | | | | | | |
| 0−15 | Organic matter | Peat | Gley layer | Cryometamorphc layer |
| 20−30 | 11.8 | 19.8 | 19.6 | 10.2 | 6.6 | 32.0 | 48.8 |
| 30−40 | 7.6 | 20.4 | 21.8 | 13.4 | 12.3 | 24.5 | 50.2 |
| 52−60 | 13.3 | 24.9 | 13.9 | 7.1 | 12.0 | 28.8 | 47.9 |
| 60−70 | 13.4 | 23.1 | 21.7 | 11.8 | 12.7 | 17.3 | 41.8 |
| 4−2019 Folic Podzol | | | | | | | |
| 0−25 | 24.9 | 46.4 | 9.3 | 3.3 | 1.1 | 15.0 | 19.4 |
| 25−29 | 21.4 | 56.9 | 7.0 | 3.7 | 1.1 | 9.9 | 14.7 |
| 29−33 | 8.2 | 61.3 | 17.3 | 2.9 | 2.1 | 8.2 | 13.2 |
| 35−40 | 60.2 | 28.4 | 3.5 | 1.5 | 0.1 | 6.3 | 7.9 |
| >60 | 65.5 | 23.4 | 3.5 | 0.9 | 0.3 | 6.4 | 7.6 |
| 5−2019 Histic Entic Podzol | | | | | | | |
| 0−10 | 12.7 | 53.9 | 18.4 | 3.4 | 2.6 | 9.0 | 15.0 |
| 10−20 | 15.9 | 49.1 | 19.6 | 2.7 | 2.3 | 10.4 | 15.4 |
| 20−30 | 5.0 | 60.8 | 16.0 | 4.3 | 5.9 | 8.0 | 18.2 |
| 50−70 | 52.1 | 31.2 | 6.2 | 1.1 | 1.9 | 7.5 | 10.5 |

The analysis of oxalate and pyrophosphate extracts indicates an eluvial-illuvial distribution of amorphous and associated with organic matter iron compounds (Fe_{ox} – 1.35%, Fe_{py} – 0.25% in the middle part of the soil profile), with their impoverishment down the soil profile. The distribution of amorphous aluminum compounds along the soil profile is regressive and eluvial with maximum content in the soil-forming rock. Aluminum associated with organic matter-related compounds is undifferentiated along the soil profile.

The texture analysis results indicate an accumulative elluvio-illuvial type of physical clay fraction distribution with a maximum content in the humus horizon and soil-forming rock.
3.2. Gleysoils
At the foot of the western slope of the hill in the Bolshaya Erakingra River valley under the birch-larch forest, the soil of the Gleysoils group is described (Soil profile 3–2019). The profile of this soil is represented by a peat layer lying on a gleyed layer. The cryometamorphic horizon begins from a depth of 52 cm, it is represented by perennial permafrost as a mineral mass concrete-bound by ice. Thixotropy is observed from a depth of 64 cm. The soil is defined as Gleysol (Gelic).

The soil under study is characterized by a strongly acidic reaction throughout the soil profile. The soil has a high absorption capacity. The CEC in the gleyed depth and at the top of the cryometamorphic layer varies from 35.9 to 40.5 mmol kg\(^{-1}\). Ignition loss in the organic horizon is 71.0%. The content of \(\text{C}_{\text{org}}\) is 1.7% in the gleyed depth and 1.1–0.7% in the upper and lower parts of the cryometamorphic layer.

The chemical analysis results of the oxalate extraction using the Tamm method and of the pyrophosphate extraction using the Bascombe method showed a relative increase in iron and aluminium content in the upper part of the cryometamorphic layer, compared to the overlying gleyed horizon and the lower part of the cryometamorphic layer. This can be explained both by more intense cryohydrothermal processes in the upper part of the soil profile and by processes of soil weathering and migration of substances in the soil profile along the defrosting gradient.

The results of texture analysis indicate an eluvial-illuvial type of distribution of the physical clay fraction with a maximum content at the bottom of the gley layer (50.2%).

3.3. Podzols
No Cambisols have been found on the northern and northeastern slopes of the Tukuringra Range along the Gilyuy River. Shallow rank soils and rock outcrops have been identified throughout the area. Soils with a thick moss cover (30–40 cm) are formed on low gradient slopes. Excavation of soil pits in these areas is complicated by a layer of perennial permafrost (more than 15 cm thick) under the peat horizon, which is practically immune to physical impact. Thawing of the permafrost layer in July (at ambient temperatures of 20–25 °C) appears to be minimal and does not exceed 3–5 cm under the forest cover and 7–10 cm in open areas.

The soil pits were made in a well-drained area, in the lower part of the northern slope, near the ravine (Soil profile 4–2019) and within the terrace above floodplain of the Stepanak River under the fir forest (Soil profile 5–2019). Both soils have been defined as shallow Podzols.

The upper part of the profiles of the described Podzols is represented by a dry peaty layer. The formation of these soils on the colluvial sediments is reflected in the lower part of the profiles as turbated material deposits of light soil. In the terrace above floodplain soil, the lower part of the profile is composed of round stone with traces of seasonal frost (in the form of ice lenses and veins) and ferrous films (figure 2) on the lower surface of the round stones. The formation of these films is associated with processes of redeposition of iron hydroxides as a result of long-term freeze-thaw cycles [15]. The described soils have been defined as Folic Podzol (Soil profile 4–2019) and Histic Entic Podzol (Soil profile 5–2019).

The Folic Podzol under study has a strong acidis reaction throughout the soil profile. The upper part of the soil profile has a high absorption capacity (CEC 29.9–45.7 mmol kg\(^{-1}\)), with a drop of this indicator to 21.5–21.8 mmol kg\(^{-1}\) in the colluvial sediments. Ignition loss in the organogenous layer reaches 54.3%.

The determination of the content of iron and aluminum compounds has shown that their maximum content is confined to a depth of 29–33 cm (Fe\(_{\text{ox}}\) – 1.20%; Al\(_{\text{ox}}\) – 0.67%; Fe\(_{\text{py}}\) – 0.15%; Al\(_{\text{py}}\) – 0.06%), while the distribution of these compounds throughout the soil profile is of eluvial-illuvial type.

The content of physical clay and silt fractions is evenly accumulative in nature. The soil is characterized by light texture composition.

Histic Entic Podzol soil is characterized by an acidic reaction throughout the profile. The soil has a high absorption capacity (CEC 38.7–59.3 mmol kg\(^{-1}\), gradually decreasing to an average level of colluvial
deposits (23.4 mmol kg\(^{-1}\)). The degree of soil base saturation is low (32–39\%), with an average degree in colluvial deposits (60\%).

The analysis of amorphous iron and aluminum compounds shows that their distribution in the soil profile is similar to the considered earlier Folic Podzol (Section 6–2019), with a maximum content at 20–34 cm deep.

Similarly to the case of Folic Podzol described above, this soil has a light particle size distribution. However, during seasonal frost periods when frost acts as a confining stratum, it is possible to observe gleization processes of low intensity in the soil profile.

4. Conclusion
The following soil types were identified based on the field and laboratory data from the mountain-forest landscapes of the Zeysky Nature Reserve: Cambisols, Gleysol (Gelic), Folic Podzol, and Histic Entic Podzol. All these soils have a thin profile and are characterized by a close proximity of the parent rock to the surface.

Due to the formation of Cambisols on warm slopes of the southern exposure and more active processes of organic matter metamorphization, a well-formed humus horizon is identified in the soils. The middle part of the soil profiles is aggregated, clayed, and browned, which is evidence of intensive processes of metamorphism and mineral mass weathering.

Various forms of cryogenic processes are clearly observed in the described soils on the western and northern exposure slopes. This can be explained by a wide distribution of perennial and seasonal frost in this area. Permafrost is also responsible for the process of conservation of plant remains entering the soil and, as a result, formation of a peat horizon at the top of the soil profiles.

In the Gleysol (Gelic) profile, cryogenic structure formation and pedoturbation processes are clearly diagnosed. In the transition zone from permafrost to gley soil, there is an accumulation of iron and aluminum compounds, as well as physical clay and silt, which is due to the intensive cryogenic migration of substances along the thawing gradient.

The Podzol soils described within the northern exposure slopes are characterized by a light particle size distribution and strong mineral material turbulence at the bottom of the profile caused by their slope position and formation on colluvial sediments. The freeze-thaw processes on the lower surface of rocks and gravel result in redeposition of iron hydroxides. Based on the distribution of amorphous iron and aluminum compounds in these soils, it is possible to speak about the formation of illuvial-ferrous layers.
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