Anthropogenic land degradation within the right-of-way of overhead transmission lines (Western Siberia, Russia)

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Highlights:

- Land mapping was carried out in a series of 50-year ultrahigh voltage lines.
- The structure of the soil cover of the land in the ROW is established.
- Anthropogenic soils are resectozems, stratozems, stratolite and abrazem.
- The total area of anthropogenically changed soils is 27.5% of the entire study area.

Running title: Soil degradation in transmission line rights-of-way

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Abstract

Anthropogenic impacts from the construction and operation of high-voltage transmission lines on a land in a right-of-way (ROW) result in soil cover (umbric albeluvisols) disturbances varying in scale, age and origin. The following main types of anthropogenic soils were identified within the ROW: filled soil (stratozems and stratolite), slightly disturbed resectozem 1 (umbric albeluvisols), moderately disturbed resectozem 2 and abrazem. The areas of disturbed soils are superimposed on the natural heterogeneity of the forest soils. We found that soil diversity within a ROW consists of 2.2% filled soils, 3.9% resectozem 1, 11% resectozem 2 and 10.4% abrazems. The total area of anthropogenically changed soils is 27.5% of the entire study area. Soil degradation causes resectozem 2 and abrazem. An increase in a surface slope angle till 2°–4o results in the growth of moderately degraded areas, whereas, an increase of more than 10o leads to highly degraded areas. The degree of soil cover degradation in the ROW is 3 out of 5. The form factor of site occurring during construction has a modal value of 0.8–0.9, whereas, that during operation is 0.7–0.8. This suggests that round shapes are predominant during construction, and elongated and angular shapes become more common during an operation. Contours of filled soil areas are significantly more rounded than those of the abrazems' areas. Currently, the soil cover contains accumulated traces of degradation. Thus, the cumulative potential for soil degradation accumulated over the past 60 years of intensive economic development must be considered.

Keywords: deforestation, geomorphological, overhead transmission lines, right-of-way, *s*oddy-podzolic soils, soil degradation

1. Introduction

Forest resources are becoming increasingly important not only as sources of food, wood, paper, and medical herbs, but also for their role in ecosystems (Balvanera et al., 2006), such as providing habitats for wild species (Chornesky et al., 2005; Folke et al., 2004) and performing hydrological and carbon-depositing functions (Diaz et al., 2003; Diaz et al. 2005; Bunker et al., 2005). Forest depletion presents serious ecological (Bogaert, Ceulemans, & Salvador-Van, 2004), public health, and economic problems (Atkinson et al., 2012), and can adversely affect human lives (Ahrends et al., 2010). Therefore, complete information on the scale of forest degradation and its causes is necessary to develop a strategy and make decisions related to restoring degraded forests (Bahamóndez et al., 2009; FAO, 2011a).

The demand for land degradation assessment under different natural conditions is increasing (STK4SD, 2015; Vågen et al., 2016). Anthropogenically changed soils are of particular interest in Russian soil classification (Shishov et al., 2004). Anthropogenically produced soil has lost its natural structure; however, natural soils that have been anthropogenically changed preserve some of those characteristics. These types of soils have not been sufficiently studied to date (Volungevičius and Skorupskas, 2011).

Specific ecological factors are at work under high-voltage lines (Kaskevich and Plekhanov, 2003), which must be considered when reclaiming disturbed soil or for agricultural use of land under transmission lines (e.g. pastures, hayfields, or beddings). Despite this, information in this area remains scarce. For instance, electromagnetic fields are not known to have any negative effects on soil microbes or crops of corn and winter wheat (Soja et al., 2003).

The situation is complicated by the fact that soil forming factors, which are unique for each protection zone or ROW, depend primarily on the existing anthropogenic load and allocated facilities. ROW parameters are determined by the maximal electromagnetic field value of 20 kW/m under the wires and a minimal one at the edge of ROW (<1 kW/m). A high-voltage transmission line of 500 kW has a ROW that is 60 m wide, and a single corridor may have two or even four lines. In such a case the width of the ROW would increase many fold. There should not be any forests in this zone, as this would act as a hydrothermal factor influencing soil cover formation. These specific environmental conditions are formed beneath overhead transmission lines.

Soil degradation is primarily caused by heavy construction vehicles used to remove trees from the ROW, as well as for trailing, timber transport, and uprooting. However, evidence of these mechanical soil disturbances can be seen currently in the form of regions with immature soil formed under anthropogenic impact (embriozem).

The purpose of this study is to investigate pedodiversity in the ROW of overhead high-voltage transmission lines resulting from natural processes and construction/operation activities within the boreal forests of Western Siberia.

2. Materials and methods

The study area is located between the Yaya & Kiya rivers of Western Siberia (Russia), on the macroslope of the Archekassk ridge, in the area of the village of Lomachevka (Kemerovo region. This region belongs to the forest-steppe zone of the Kuznetzk Alatau foothills. Dark-colored soils (chernozems, meadow-chernozems, and dark gray soils) are predominant, and soddy-podzolic soils (umbric albeluvisols) occur as a belt on the flattened central area of the ridge macroslope. Soils with a second humus horizon are widespread in this region.

This research is aimed at studying soil cover disturbances due to technogenic activities within a high-voltage transmission line ROW. The study area is near Lomachevka village (56.14°N, 86.84°E). The overhead transmission line (500 kW) and substations Itatskaya and Novo Anzherskaya N 524 (the cadastral number of the ROW is 42.00.2.41) were commissioned in 1967. The studied ROW area is 760 m long and 65 m wide and includes three transmission line poles.

The studied transmission line ROW is 60–65 m wide, and is used on a limited basis by famers for farm machinery access, pasturing of livestock, and haymaking) (*Zakharchenko* & *Zakharchenko,* 2006). The study area is on the western macroslope of Archekasskiy Ridge. The absolute elevations of ridge watershed range 180–220 m above sea level from west to east and the relative elevation of the ridge is 100 m.

Within the transmission line ROW, soddy-podzolic soils have an eluvial horizon (El) with gray spots at the bottom, a second humus horizon (El Bhh), and an illuvial horizon (Bt; argillic) (*Zakharchenko* & *Zakharchenko,* 2006). The morphological structure and chemical and physical properties of these soils have been thoroughly analysed.

The morphological description of the soil profile reveals notable variability of the horizon boundaries in the eluvial part of the profile. The presence of neoformations such as small iron and iron-manganic nodules in the eluvial and illuvial horizons indicates the profile's hydromorphic features. The depth of the humus horizon, including the soddy layer, is 12 cm, with tongues reaching to 14 cm. Soil density is less than or equal to 1.0 g/cm3 (table 1).

The organic carbon content is 3.44%, and abruptly decreases down the profile. Density increases in the eluvial horizon, forming a clear boundary between horizons AY and El.

The eluvial horizon is identified as a whitish layer 5 cm thick. An increase in the SiO_2/Al_2O_3 ratio compared with that in the underlying and overlying horizons is observed. In terms of particle size composition, the eluvial horizon is characterized by low clay content and a slight increase in silt content. The El horizon's boundary with the ElBhh horizon was morphologically identified by its color (whitish and grayish brownish) and heavier texture (clay content: El, 15.88%; ElBhh, 20.56%). The appearance of brownish hues in the El Bhh horizon is accompanied by decreases in the SiO_2/Al_2O_2 and SiO_2/R_2O_3 ratios.

The transitional horizon (ElBt) contains no gray due to a significant decrease in organic carbon content, going from 1.05% in the ElBhh horizon to 0.57% in the ElBt horizon, and heavier texture, with clay content ranging from 20.6 to 38.9%).

The boundary between the ElBt and Bt horizons is less obvious in the color of the structural aggregates (brown and dark brown); however, the cutans differ in these horizons, with whitish cutans in the ElB1 horizon and bluish gray or brown cutans in the Bt horizon. Particle size composition and molecular ratios reflect the initial lithological heterogeneity of parent rocks in the model plot. The coarse silt fraction (0.05–0.01 mm) is predominant in the particle size composition, and the silt content decreases and clay content increases down the profile. The clay content abruptly increases in the illuvial horizons. The underlying horizon is distinguished by abundant medium- and coarse-grained sand and molecular ratio changes.

The vegetation cover of the ROW has a mosaic pattern that is determined by a combination of anthropogenic and natural microcenoses. The number of wood and grass species decreases, whereas the number of forest-meadow and meadow plant species increases within the undisturbed or slightly disturbed areas of the ROW. The abundance of meadow plant species, which are identified by their projective cover and vegetative shoot heights, significantly increases.

We built a grid that illustrates the anthropogenically changed soils based on calculations of the hierarchical structure of ROW soil heterogeneity (*Zakharchenko, Alexeev & Ipatova, 2016;* Zinck et al., 2016*)*. The distance between the grid nodes was 40 m and the boundaries of soil bodies were identified at a 1:1000 scale. The ROW was divided into square sites measuring 40 × 40 m centred on the central wire. As the ROW is more than 40 m wide, lanes 20–30 m long were allocated on the edges, depending on the position of the forest boundary. To contour lines of soil disturbances and ruts of complex shape on a map, we divided each site into four parts. To mark the territory, an azimuth circle and a 40-m-long metal measuring tape were used. The morphological structure of disturbed soil was described within each site. The composition of anthropogenic soils and the area occupied by a certain type of disturbance (%) with respect to the entire study area were visually defined (Land Resources and Land Management Committee of the Russian Federation, 1994). We then evaluated the degree of disturbance within the mapped area based on the predominant soil type, and we plotted the area contours on graph paper, with the origin of the soil disturbance (construction-related or operation-induced) being indicated if possible.

The contours of each site were imposed on a high-resolution satellite image using AutoCAD software. We then indexed each contour and recorded those values. Samples were collected from 384 sites and the following site parameters were considered: area, perimeter, and contour starting point coordinates.

We used the calculated variable value, i.e. form factor, to characterize the shape of the selected sites. The form factor is calculated as

$$F = \frac{4\pi S}{P^2},$$

where S is the site area and P is the site perimeter.

The form factor enables estimates of how close the shapes of the contour boundaries are to a circle. Ideally, when $F = 1$, the contour shape is close to a circle. For a triangle $F = 0.64$, and the more elongated a shape is (uneven borders), the lower its F value is.

The random variables and characteristics of study area contours and perimeters demonstrate a dramatically abnormal power distribution. Therefore, for statistical analysis of the structural characteristics we used non-parametric statistical analyses such as the Mann-Whitney and Kruskal-Wallis tests are used.

We used a freely available satellite image (Google, 2016) as a topographic base for mapping anthropogenically changed soils within the ROW. Mapping and data statistical analysis were carried out using AutoCAD and STATISTICA software.

3. Results

Specific construction operations result in mechanical soil disturbances with repeated size, form, location with the respect to poles and central conductors. These disturbances include filling (strpatozems and stratolites) and severely degraded (abrazems) contours.

Strpatozems are soils with filling layers of more than 40 cm and stratolites are bedrock outcrops or their fillings. Filling disturbances are formed by soil excavation at poles and are conditioned by filling soils.

Abrazems are soils that are partly or completely without a soil profile. The dirt roads have high topsoil density (1.20–1.50 g/sm^3); however, their properties have not yet been studied yet as they occupy insufficient areas.

In incidental construction operations, the disturbed soil areas take the form of sporadic and randomly distributed spots over the ROW and elongated ruts as well as disturbances formed when felled trees are moved. While removing trees more than 50 cm in diameter, sporadic spots of degraded soil appear due to cutting part of soil profile up to El horizon of the soddy-podzolic soil.

The two soil subtypes are distinguished by different topsoil cutting depths. Resectozems are soils that partially or completely lack an upper horizon but that still retain their typical identity. Albeluvisol resectozems can be divided into two subgroups: slightly disturbed (resectozems 1) and moderately disturbed (resectozems 2). As seen in Figure 1, resectozems form sporadically scattered spots in the ROW, but sometimes form complex shapes on the edge of abrazems. Under these conditions there are also abrazems.

Embryozems, which are semimature soils formed on the surface of man-made soils, form on the surfaces of disturbed areas.

Soils in the overhead transmission line ROW have parts of their profiles that are characteristically modified. Accordingly, the classification of anthropogenic can be is adapted to the predominant type of natural soil and the specifics of mechanical disturbances.

Resectozems 1 are soils that have no part of the normal humus horizon. Soil density ranges from 0.8 to 1.0 g/cm^3, which promotes fast restoration and area reduction over a 20 year period. Organic carbon content in the layer 50 cm from the surface changes from 4.8% to 0.5% (table 2).

Resectozems 2 are completely without a humus horizon and the eluvial horizon is present on the surface, giving these soils a whitish color. The density of the upper part of the surface horizon ranges from 0.8 to 1.2 g/cm^3, and humus content ranges 2.8%–3.9% in the 0–15-cm layer.

Strotolites are soils formed by excavation under the overhead transmission lines and are associated with filled soils. Organic carbon content is 2.3%–5.7% at 3–8 cm. In the filling soil (litozems), organic carbon ranges from 0.3% to 3.8% at 25 cm below the surface.

Abrazems are soils with completely disturbed eluvial horizon (in this case El). The abrazem density of the surface horizon is 1.0–1.5 g/cm^3, and the high density of surface horizons prevents the rapid growth of vegetation, which hinders natural soil recovery. In abrazems, organic carbon enters through washing out of undisturbed and slightly disturbed areas as well as pit walls. Its organic carbon content is 2.7%–6.5%.

Embryozems are soils formed under the overhead transmission lines, and they have smooth borders of round shapes. Humus is actively accumulated in the fill grounds, where the density is comparable to that observed in the humus horizon of undisturbed soil (0.821–0.992 g/cm^3).

In autumn and spring tractor passages poach the wet soil – tracksol. Soil horizon thickness decreases insufficiently, but surface boundaries form and humus horizon changes. Soil is expelled from humus and eluvial horizon. Ruts can be formed by tractor undercarriage as a result of stringing and stretching overhead transmission line. Ruts and field roads are of high density (1.2–1.5 g/cm^3) and occupy small areas, therefore, their properties have not been studied, but were described in morphological soil study.

To simplify the display of anthropogenic soil on the map, four groups with similar properties were allocated (figure 1).

The figure shows that after the construction of the transmission line (1986), the land degradation spots are significantly larger than those observed in the ROW area of the 1967 transmission line. The shooting was carried out in one year. Consequently, after 20 years of self-restoration of lands from 1967 to 1987, large spots are fragmented into many small ones.

The 2016 satellite image shows that there are light degradation spots on the 1986 power line. Preservation of degradation spots is caused by soil erosion on the slope.

1. Stratolites and stratozems are united in the group of filled soils.
2. Resectozem 1 is defined as slightly degraded soil,
3. Resectozem 2 is labeled as medium degraded soil.
4. Abrazems are referred to as severely degraded soils.

In addition, construction and operational disturbances of the soil cover, as well as ruts made by track vehicles and field roads, are shown.

The zones of predominating rectozem 1 are referred to slightly degraded soil, whereas the zones with rectozem 2 predominating and presence of ruts are considered to be medium degraded. Those with abrazem predominating and ruts are severely degraded.

At the time of the disturbed soil mapping, the soil age was 20 years. The restoration rate of the upper horizon depends on the substrate where there is some development (table 3). The embryozems were classified into 4 groups according to their natural development rate of humus layer thickness. Resectozem 1 has been almost completely restored during this period. The thickness of newly formed humus horizon of resectozems 2 is 1–3 cm, that of abrazems is 2–5 cm whereas that of filled soils (Stratozem+Stratolit) under transmission line poles is up to 5–7 cm.

Filled soils are stored near the transmission line poles; however, there is not much soil with a bulk layer thickness greater than 40 cm. Such soils make up 2.2% of the total area and have an average maximum area of 69.5 m^2. Additionally, the number of sites per unit area is minimal (5.7 site/ha).

Slightly degraded soils occupy a small area. This can be explained by the fact that anthropogenic soil mapping was conducted 20 years after the transmission lines were constructed. During this period, the humus horizons restored close to natural thickness in most cases. The occurrence of such soils is higher than stratozems because of the greater number of small and sporadically distributed sites over the ROW. Sometimes slightly degraded soil areas surround contours that were exposed to moderate or heavy mechanical loads.

Resectozems 2 occupy the largest proportion of the total area (11%), and their occurrence is 17.3 sites per hectare. These soils have vegetation and regenerate most slowly. The average area per site of this group is 63.9 m^2.

Abrazems occupy 10% of the ROW; however, their rate of occurrence is 22.8 sites per hectare, which is the highest in the ROW. This is due to the large number of disturbed areas ($N = 220$).

The extent land of ROW degradation can be assessed using exposed rock area as a criterion (Land Resources and Land Management Committee of the Russian Federation, 1994). A degradation degree of 0 amounts to 0%–2% of the total area; at 1, the area is 3%–5%; at 2, the area is 5%–10%; at 3, the area is 11%–25%; and at 4, the area is >25%. Speaking objectively, although they have the remains of the illuvial horizon (Bt), abrazems are essentially a completely disturbed soil profile. If we assume that the abrazems cut all soil, the degradation degree of ROW soil under overhead transmission lines is between 2 and 3, with a maximum possible extent of 5.

Distinguishing three degrees of degraded forest soils (slightly, moderately, and severely degraded) reveals the relationship between the degradation degree and slope angle of the ROW surface. With a surface slope angle of 0°–2°, the area of moderately degraded soil decreases with an increase in slightly degraded soil. At a slope angle of 2°–4° the area of slightly degraded soils decreases and there is a four-fold increase in moderately degraded soils.

This increase occurs because a bulldozer bucket horizontally digs the ground deeper than a slope angle of 1°–2°. Hence, at slope angles of more than 10º, bulldozer buckets dig even deeper, increasing the area of severely degraded soil many times over because of a decrease in moderately and slightly degraded areas.

Soil disturbances during construction amounted to 1.43 hectares and during operation they were 0.38 hectares, which translates to 19.73% and 5.26% of the research area, respectively. Random variables of sampled values from the area and perimeters have a power-series distribution; therefore, we applied non-parametric analysis methods. Size comparisons of samples from disturbed areas using the Mann-Whitney U test showed that the difference between samples is significant at $p < 0.05$. The distribution of disturbed areas during construction ($N = 216$) has a greater variety in size and shape ($U = 11657$; $Z = 6.01$; $p < 0.05$) than during operation ($N = 168$). A comparison between anthropogenic soil types of the disturbed areas revealed significant differences between resectozems 2 and abrazems.

The form factor of the construction disturbances has a modal value of 0.8–0.9, whereas for operation it is 0.7–0.8. This suggests that round shapes are predominant in the first cases, whereas the shapes are mostly elongated and angular in the second one. In terms of form factor, the contours of filled soil areas are significantly more rounded ($U = 15660$; $Z = 2$; $p < 0.05$) than those of abrazem areas.

4. Discussion

Most of the research on land degradation concerns desertification, erosion, salinization, and anthropogenic impacts (Xie et al., 2020). Ecological problems of Grassland are known (Liu et al., 2017). Logging lands are degraded (Cambi et al., 2015).

The impact of construction equipment on natural lands during the construction of linear objects occurs in all parts of the world (Qing. & Qing, 2013). In this case, the violation of land integrity by running systems and construction equipment units occurred during the construction of high-voltage power lines 53 and 34 years ago. Natural soil profiles were partially disturbed and parts of the soil horizons were lost, with increasing depth of impact. Additionally, land reclamation was not carried out in the past. As a result, a complex of degraded soils was formed, traces of which are visible in modern satellite imagery (Figure 3).

The theory of land degradation neutrality is timely (Cowie & Baron, 2018). It should consider the cumulative potential for soil degradation accumulated over the past 60 years of intensive economic development. Degraded soils with reduced fertility should be remediated to reach an equal extent of improvement. ROW soil diversity is not confined to anthropogenic soils, but rather is complemented by the natural heterogeneity of boreal forest soil cover. Impacts on forest soil have been described in many works, and it has been shown that the soil retains traces of previous development stages, something known as soil memory (Phillips & Marion, 2005; Daněk et al., 2016; Targulian & Bronnikova, 2019).

The forest in the ROW is destroyed because of power line construction and operation, thus the vegetation that develops is of the meadow type. The heterogeneity of ROW soil cover that formed on the forest zone soils consists of two components: the inherited parcel structure of forest ecosystems and anthropogenic load. However, the current soil classification based on existing diagnostic methods neglects to reflect these aspects. Thus, it is necessary to develop standards to assess anthropogenic soils formed during construction and operation of high-voltage transmission lines.

5. Conclusions

The anthropogenic impact of high-voltage transmission lines on ROW land results in soil cover heterogeneities of different scale, age, and origin. This provides a basis for diversity of soils in terms of morphology and general physical and chemical properties.

We have shown that anthropogenic ROW soils can be divided into four main types: 1) filled soils (stratozems and stratolite); 2) resectozem 1 (umbric albeluvisols); 3) resectozem 2 (umbric albeluvisols); and 4) abrazem. Disturbed areas are superimposed on the natural heterogeneity of the remaining forest soils.

Humus content in anthropogenic soils varies significantly, as humus comes to the soil with either filling soil or from surrounding undisturbed or slightly disturbed soils.

Increases in the surface slope angle from 2°–4° increases significantly raise the area of moderately degraded soil, and at slope angles of more than 10º, severely degraded soil prevails.

We found that the pedodiversity of ROW under high-voltage transmission lines consists of 2.2% filled soils, 3.9% resectozems 1, 11% resectozems 2, and 10.4% abrazems. The average area of one site is highest for filled soils (69.5 m^2). The anthropogenic soil area of the ROW is 27.5%, and the degree of soil cover degradation is 3 out of 5.

Disturbances during construction are more extensive and varied in shape than those formed during operation. Comparison of the anthropogenic soil types of disturbance areas reveals significant differences in resectozems and abrazems. Based on to the form factor, the contours of filled soils area are found to be more rounded than those of the abrazems area.

Thus, there are anthropogenic soils that formed due to laying cuttings and the construction and operation of high-voltage transmission lines in the ROW. Over 50 years of exploitation, soils did not recover their natural fertility, but rather are referred to as degraded soils. Thus, it is necessary to design measures to remediate soil at the design stage in forest territories where there are trees with trunk diameters of at least 50 cm.

The cumulative potential for soil degradation accumulated over the past 60 years of intensive global economic development in all geosystems should be taken into account.

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