АГРОХИМИЯ И ПОЧВОВЕДЕНИЕ

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Denis A. Sokolov[1], Vladimir A. Androkhanov[1], Evgeny V. Abakumov[2]

[1]Institute of Soil Science and Agrochemistry, Siberian Branch of the Russian Academy of Sciences, Novosibirsk, Russian Federation
[2]St. Petersburg State University, St. Petersburg, Russian Federation

Soil formation in technogenic landscapes: trends, results, and representation in the current classifications (Review)

For hundreds of years, humans have been a soil formation factor. With the recent industrial development of vast territories, the formation of soils in technogenic and post-anthropogenic conditions requires more attention. This study reviews the literature on the soils of human-transformed or human-made landscapes (technogenic landscapes), in which soil formation starts on a new technogenic substrate. Such soils may occur in different bioclimatic conditions. We focused on processes that govern soil morphology and the subsequent transformation of these soils. Often, the soils of technogenic landscapes are characterized by high bulk density values and by the presence of dense contact. Their properties are affected mainly by organic matter accumulation (humus, litter, and peat). The paper also covers approaches to the reclamation of technogenic landscapes, the main stages, and partly the reclamation options. It is noted that the efficiency of reclamation activities depends on the available resources and timely decision-making. We assessed the efficiency of soil reclamation methods and suggested technogenic landscape survey techniques. The major approaches to soil classification in technogenic landscapes in national and international soil classification systems are briefly discussed, and an approximate correlation of soil names used in different systems is suggested. All considered classifications provide the opportunity to assess the soil properties and specifics of soil formation in technogenic landscapes. However, in most studies, the soil diagnostics are limited to top-order taxa only.

The paper contains 3 Figures, 2 Tables, and 140 References.

Keywords: Soil formation; technogenic landscapes; reclamation; soil classification; coal mine; dump rock; Technosol

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Introduction

The development of the post-industrial economy does not reduce industrial output or the rate of mineral extraction. On the contrary, the manufacturing productivity increase is accompanied by the transformation of large natural landscapes into technogenic barrens (technogenic landscapes). The formation and structure of technogenic landscapes are governed by human engineering activities to extract and process minerals [1]. Engineering soil transformation has the most significant impact on soils compared to agricultural and urban cases [2] because it leads to a drastic transformation not only of soils themselves but also of all soil formation factors. Soil formation in technogenic landscapes is accompanied by biocenotic succession [3], as well as changes in microclimate, initial substrate properties, and terrain features [4]. As opposed to human-transformed (disturbed) soils, where the natural processes are just corrected, soil-forming processes in technogenic landscapes utilize the “new” substrate [5].

Although some countries faced disturbed area problems as early as the 19th century, technogenic landscapes have become an object of soil research relatively recently. It was facilitated, firstly, by a significant increase in environmental footprint in the second half of the 20th century, and secondly by gaining experience in soil reclamation [6]. Until recently, the research on industrially disturbed territories has covered, mainly, the countries of Europe, the former USSR, and North America. By the beginning of the 1970s, technogenic landscapes were studied in the USA [7, 8], the DDR [9], Great Britain [10], Germany [11], Czechoslovakia [12], and Poland [13]. In Russia, as reported by the Public Committee for Safe Industrial and Mining Practices, by 1965, the reclaimed area exceeded 60.000 hectares [14]. In recent decades, a sharp increase in mineral deposit extraction has occurred in developing countries, so the geography of research has expanded significantly to cover China [15–17], India [18–20], South America [21–23], and Africa [24, 25].

The ever-increasing interest in technogenic landscapes is also related to their significant impact on adjacent areas. Thus, the risk of extreme flooding is higher in areas of intense mining [26–28]. Technogenic landscapes are also subjected to erosion and solifluction processes [21, 29]. Drain water ingress into migration flows affects ground and surface waters [30–32]. Artifacts containing carbonaceous material are prone to spontaneous combustion [33], which reduces the air quality [34].

Technogenic landscapes have not only negative but also some positive effects. In some cases, the fertility of mining waste is higher than that of natural soils [35]. There are cases when soils suitable for plant growth are produced from mining waste. Such waste is prepared by grinding stony fractions, adding active organic matter, and, sometimes, pH neutralization [36]. In the soils of technogenic landscapes, a particular field of study is their carbon sequestration capacity [37–39].

Regardless of the type of activity that produced technogenic landscapes and soils, there are always geochemically (and sometimes geomorphologically) unstable formations. The forces driving the balancing of their surface properties with environmental factors are not only the soil formation drivers but may be caused by pedogenesis. For this reason, the studies of the soils of technogenic landscapes are of great interest.

This review analyzes the existing global approaches to soil formation in technogenic landscapes, their reclamation, and their placement in the soil classification system. We consider the soils created through self-remediation or by reclamation of mining waste dumps, mineral processing waste, construction waste, and marine sediments deposited onshore during dredging operations. We paid particular attention to coal mine dump soils, as coal mining is the leading industry that expands technogenic landscapes. In addition, coal is mined on all continents except for Antarctica and in every climatic zone.

Characteristic features of soil formation in technogenic landscapes

Physical properties of parent materials. Compaction and decompaction. As technogenic landscapes are formed, significant volumes of various substrates are extracted or moved by heavy machinery. As a result, soil formation usually occurs on over-compacted substrates. Even when the process does not include surface leveling or the use of heavy equipment (for example, in water development projects), the soil density of technogenic landscapes is still higher than the density of natural soils in the adjacent areas [40]. While the density of the technogenic landscape soils composed of sandy, loamy and clayey substrates (loose rocks) is in the range of 1.1-1.8 g/cm^3, it can reach 2.5 g/cm^3 for stony surfaces. In both cases, as soils are formed, the density does not remain constant and changes through two alternating and opposite compaction and decompaction processes [41].

Technogenic soils compaction often continues even after a human activity is completed. For instance, stony soils continue to be compacted regardless of the climatic conditions through packing (shrinkage) of the soil-forming substrate (Table 1). Extra soil compaction occurs when the soils are used for agriculture [42], and, subsequently, as polyculture is replaced by monoculture [43]. The high density of loose soils in technogenic landscapes leads to low water permeability. Therefore, the soil formation on the surface of drill cuttings in a humid climate is hydromorphic [44], which is also detected in moderately humid areas covered by a fertile soil layer [45]. Reducing processes identified by increased methane emission [46] or formation of ferromanganese nodules [47] are detected in the soils formed on stony substrates.

Decompaction occurs as a result of root system development initiating the soil structure formation [15]. Because loamy soils contain more material suitable for structure formation than stony soils, their deconsolidation is faster.

Spatial and vertical heterogeneity. Heterogeneity is typical of the soils of technogenic landscapes. Spatial heterogeneity (Fig. 1) is found at sites where the surface is composed of various substrates [17, 48]. A pronounced profile heterogeneity is formed during reclamation, as rocks are laid layer-by-layer. It is also produced as young soil mature. In a humid climate, the textural differentiation of the profile of the technogenic landscape soils is caused by eluvial and illuvial processes [49]. In technogenic formations composed of stony rocks, the soil profile differentiation is due to physical, biophysical, chemical, and biochemical disintegration [50]. It is noted that the intensity of disintegration of coarse rock fragments is higher in arid areas, while for gravel and sand, it is higher in areas with optimal moisture content [51].

Fig. 1. Scheme of the formation of technogenic landscape spatial heterogeneity in surface mining

Organic matter accumulation. Soil profile differentiation by organic matter content is a distinctive feature of most technogenic landscapes. Organic matter can be both inherited from soil-forming rocks (lithogenic), e.g., in the soils of coal mine dump, or generated by soil and biological processes. As many authors note (Table 1), the soils of technogenic landscapes, regardless of the rock composition and climatic conditions, feature intense organic matter accumulation rates exceeding those in natural soils. In the areas where organic matter accumulation occurs in zonal soils, organic carbon in technogenic landscapes is fixed by humus accumulation.

High organic matter accumulation rates are also found in the soils with soil-forming rocks enriched with lithogenic organic matter [61]. The accumulation of humus increases from stony to sandy [58] and further to loamy rocks [82]. In areas where the formation of thick humus horizons is not a feature of the zonal soil formation, the intensity and peculiarities of organic matter stabilization processes in the soils of technogenic landscapes are determined by the lithological properties of the substrates [83]. In the soils enriched with fine fractions (< 0.01 mm), high organic matter accumulation rates can also be found in subtropical and tropical climates [19, 64]. In such areas, they are also found on stony substrates capable of producing fine particles upon weathering [20, 23].

It should be noted that humus accumulation is not the only process of organic carbon accumulation in the soils.

Table 1

Key factors and processes contributing to technogenic soil properties

Key properties	Major processes	Manifestation	Soil-forming rocks	Climate	Authors
Density	Compaction	Rolling	Total	Everywhere	Shikula, Drugov, 1974 [52]; Jacinthe et al., 2006 [46]; Evans et al., 2013 [53]; Ahirwal, Maiti, 2016 [20]
		Shrinkage	Mostly stony	Everywhere	Sokolov et. al., 2015 [54]; Ahirwal, Maiti, 2016 [20]; Ruiz, 2020 [23]
			Loamy rocks	Humid	
	Decompaction	Structure formation	All non-phytotoxic, mostly loose	Everywhere	Shikula, Drugov, 1974 [52]; Zhao et al., 2013 [15]; Frouz et al., 2017 [55]; Ruiz et al., 2020 [56]
Heterogeneity	Textural differentiation	Disintegration	Mostly stony	Everywhere	Kusov, 2007 [50]; Sokolov et al., 2012 [51]; Sokolov, 2019 [41]
		Lessivage		Humid	Daniels et al., 2004 [49]; Daniell, van Deventer, 2018 [24]; Wang et al., 2017 [57]
		Podzolization		Strongly continental humid	Sokolov et al., 2015 [54]
	Organic matter accumulation	Humus accumulation	Non-phytotoxic, from stony to clay	Moderate and strongly continental	Burykin, Zasorina, 1989 [58]; Shugaley, 1997 [59]; Abakumov, Frouz, 2009 [60]; Vindušková et al., 2014 [61]; Uzarowicz et al., 2017 [62]; Čížková, 2018; Frouz, Vindušková 2018 [63]
			Sedimentary stony, silty, ash, and bottom sediments	Dry subtropical and tropical	Masciandaro, 2014 [64]; Maiti, Maiti 2015 [19]; Ahirwal, Maiti, 2016 [20]
				Humid subtropical and tropical	Ruiz et al., 2020 [23]; Hu et al., 2021 [65]
		Litter accumulation	Non-phytotoxic, from stony to clay	Moderate and strongly continental	Filcheva et al., 2000 [66]; Kurachev, Androkhanov, 2002 [67]; Abakumov, Gagarina, 2006 [68]; Pereverzev et al., 2007 [69]
		Coalification	Pyrite-bearing loamy rocks	Moderate continental	Solntseva, Rubilina, 1987 [70]
		Mummification	Sedimentary stony	Arid strongly continental	Sokolov et al., 2014 [47]
	Organic matter oxidation	Dehumification	Humified substrates	Everywhere	Androkhanov et al., 2000 [40]; Shrestha, Lal, 2011 [71]; Festin et. al., 2019 [25]
		Decoalification	Coal-containing loose and dense sedimentary rocks	Moderate continental humid	Rumpel, Kögel-Knabner, 2002 [72]; Rumpel, 2004 [73]; Chabbi et al., 2006 [74]
		Burning		Humid	Querol et al., 2011 [33]; Bragina et al., 2014 [75]; Sokolov, 2019 [41]

Table 1 (end)

Key properties	Major processes	Manifestation	Soil-forming rocks	Climate	Authors
Acidity	acidification	acid drainage	sulfide-containing	humid	Kuka et al., 2013 [76]; Rocha-Nicoleite et al., 2017 [21]; Ramasamy, Power, 2019 [77]; Weiler et al., 2020 [78]; Acharya, Kharel, 2020 [79]
		decarbonatization and gypsification	sulfide-bearing loose sedimentary rocks	moderate continental	Solntseva et al., 1992 [29]; Bragina, 2016 [80]; Konstantinov et al., 2018 [81]

For example, in soils on calcareous rocks within technogenic landscapes, the abundance of soil microorganisms contributes to a higher rate of particular organic matter accumulation compared to mineral-bonded organic matter. This effect increases with the soil heat [65]. When the activity of plant organic matter destructors is suppressed for various reasons, plant litter is accumulated on the surface of technogenic landscapes [66, 69]. During the formation of herbaceous ecosystems, the predominance of litter accumulation over humus accumulation is observed in the first stages of vegetation development [67]. In forest ecosystems of boreal and sub-boreal climates, litter accumulation often replaces humus accumulation [68]. Specific organic matter stabilization processes in the soils within technogenic landscapes include carbonizing plant residues in highly acidic rocks [70] and their mummification during the soil formation in arid areas [47, 54].

Organic matter oxidation. In technogenic landscapes where humus substrates form the surface, organic matter *dehumification* occurs. The upper layers of natural soils stored for subsequent use in reclamation are subjected to mineralization to a greater extent [25, 40]. The reason for this is that the bulk humus layer in the soil profile being formed is slowly involved in metabolic processes. In 30-year-old soils from Siberian coal mine dumps, the biologically active layer thickness does not exceed 10 cm. The microbial biomass and basal respiration values only come close to the background value in the topmost 5-cm thick layer [84].

Another manifestation of organic matter mineralization in the soils of coal mine dumps is *combustion* occurring as spontaneous combustion of the dumps. Combustion is not a soil process. Nevertheless, it affects both the soil-forming rock composition [75] and the properties of the soils at the adjacent sites [41]. A less intensive process of lithogenic organic matter oxidation is called *decoalification* [85]. Along with mineralization [74], decoalification involves coal carbon in the formation of humus systems and soil microbial communities [72, 73]. It is noted that the carbon balance in the soils of technogenic landscapes remains positive after the decomposition of lignite. 60% of the CO_2 released from such soils is provided by the degradation of carbonates [86].

Acidification and gypsification. The acidity of the technogenic landscape soils is also associated with oxidation processes (Table 1) Minimal pH values are characteristic of soils formed on sulfide-containing wastes of ferrous and non-ferrous metallurgy and coal mining. Oxidation of sulfides at such sites leads to the termination of plant communities [87]. In humid areas, this process initiates acid drainage, which increases heavy metal mobility [88]. When the soils are formed on carbonate rocks, exposure to acid solutions leads to leaching or decarbonatization [81]. The latter is often accompanied by gypsum formation: gypsification of the entire soil profile or the upper part [29, 80].

Soil properties and environmental conditions. The soil formation in technogenic landscapes does not always follow the trend of pedogenesis typical of zonal soils in natural conditions. The primary reason for this is the soil-forming substrate properties. The trends of local natural and technogenic pedogenesis coincide only where the properties of technogenic substrates are close to those of soil-forming rocks in undisturbed soils. This is most evident in a moderate continental climate, where humus accumulation is the leading process of soil formation on both dumps of loamy rocks and natural loamy soils. Besides, this is a primary process for the soils in hotter and more humid regions but only on rocks with a high lithogenic humus accumulation potential. Such rocks contain or can produce a sufficient amount of fine mineral material [89, 90].

The evolution of eluvial and illuvial processes leading to texture-differentiated soils is typical of humid climate areas. Illuvial processes are primarily found in stony substrates, especially consisting of rocks less resistant to weathering. However, the high density of technogenic substrates and their shrinkage can minimize the manifestation of any soil processes.

Another important feature is that the surfaces of most technogenic landscapes are differentiated in their relief, density, composition, and some other soil-forming rock properties. Under such conditions, the evolution of soils and topsoil is diversified [41], while the divergence of soil geochemical processes in time and space contributes to further isolation of evolutionary trends [91].

Reclamation of technogenic landscapes

On the practical side, the soil formation in technogenic landscapes is a transformation of the substrate properties to make them “useful” and facilitate further use of the technogenic landscapes. “Useful” functions are selected and adjusted while reclamation is in progress. Conventionally, reclamation is understood as restoring soil fertility to a degree suitable for agriculture and forestry [11]. Recently, the concept of reclamation has been somewhat changed, mainly due to expanding its goals and objectives. Today’s reclamation is the formation of a sustainable neo-landscape that meets the soil-ecological state specifications and has the soil functions defined at the design stage [92]. Such a definition suggests that the result of reclamation is creating sustainable soil cover, contributing to the reproduction of the key ecosystem components with a certain level of fertility [41]. In practical terms, results of the soil formation in technogenic landscapes should be considered through the soil-ecological efficiency of reclamation [4]. Let us explain that by *soil-ecological efficiency* of reclamation, we mean the ability of the soils of technogenic landscapes to perform the functions inherent for natural undisturbed (zonal) soils in the same area.

Modern approaches to reclamation involve four main stages (Fig. 2). At the first *planning stage*, we define reclamation goals and objectives and assess the required and available resources for implementing methods and options of reclamation [17, 57, 93].

At the engineering stage, the relief and surface layers of a technogenic landscape are formed, including horizontal surface arrangement and slope reduction. Boulder rocks resistant to supergene transformation are often used to stabilize the slopes mechanically and ensure geomorphological stability. When building flat and slightly sloping areas, it is better to cover the surface with potentially fertile substrates (PFS) suitable for soil formation. One example case is the disturbed areas of Mangyshlak and the foothills of the Tien Shan within Kazakhstan. It shows that substrates already transformed by soil formation are more susceptible to soil processes [94]. In a moderate climate, humus material of fertile soil layers (FSL), pre-stored before mineral deposit development, is used for surface backfill [38, 43, 48, 95]. Where FSL resources are in low supply, the fertile layer can be mixed with other rocks (usually loamy). It was established that the acceptable mix ratio is 50%. With 75% loam content, the ability of the soil to self-repair is sharply reduced. Adding more rocks to FSL decreases the resistance of the reclaimed soil to stress [96]. Some reclamation guidelines suggest backfill with FSL not immediately after the dump formation, but 4-5 years after; the soil will settle down and be inhabited by plant communities [97].

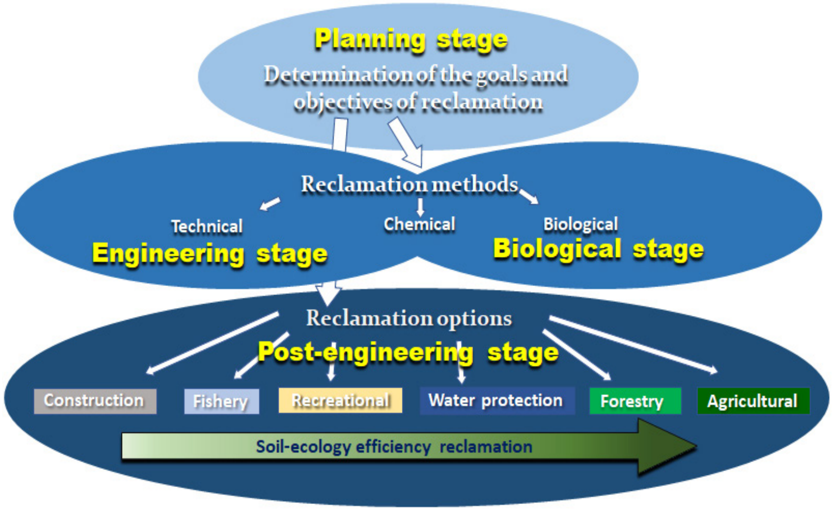

Fig. 2. Reclamation activities flowchart

When the neo-landscape body is composed of phytotoxic substrates, *chemical reclamation* is used at the engineering stage [56]. Chemical ameliorants make the root zone suitable for plant growing [64, 87, 98, 99]. They also reduce the mobility of pollutants [77]. Chemical reclamation is also used for soil improvement. The use of mineral fertilizers [46], ash [76], some organic [19, 100], and municipal solid waste [78] are widespread. Recently, particular attention has been paid to the use of coal produced by incomplete combustion of wood [18, 25], animal bones [101], or fossil coal [102] in reclamation. It was found that in climatic conditions unfavorable for humus accumulation, pyrocarbons promote the fixation of carbon and other nutrients in soils [103]. The presence of lignite particles in the soil facilitates herbaceous vegetation growth and mortmass accumulation [104].

The key objective of ***the biological stage*** is forming a layer of soil and vegetation over the surface of a technogenic landscape. The layer properties should meet the goals of reclamation. Note that some goals do not require the biological stage at all. For example, there is *reclamation for construction* when structures and industrial sites are built within a technogenic landscape. *Reclamation for fishery* provides the lowest soil-ecological efficiency. It is often limited to slope flattening and creating shallow ponds for subsequent fish farming [16]. Overgrowing of technogenic landscapes can be considered as a particular case of reclamation. This option also excludes the biological stage. Surrounding ecosystems, which usually have a substantial biological capacity, promote vegetation growth on the soil-forming substrate [59]. For coal mine dumps, the soil-ecological efficiency of overgrowth is often higher than conventional forestry and agricultural reclamation technologies [22, 105].

The post-engineering stage. With the proximity to large settlements, a wide variety of rock compositions, and landforms (some of them are unsuitable for any further use), in some cases, technogenic landscapes are promising for *recreational (tourist) reclamation*. For example, dumps are "technogenic mountains", so they are attractive for residents of plain territories. The reason for technogenic landscape attractiveness is their specific macro- and mesorelief and the presence of various rocks and vegetation areas that may form a wide range of forest, meadow, and rupicolous ecosystems. The soil-ecological efficiency of this option depends on the properties of stored substrates and the intensity of the subsequent use of an area [93].

Reclamation of a technogenic landscape for *water protection* aims to maintain the sustainable functioning of water bodies, both natural and created through industrial activities. This option rarely covers the entire technogenic landscape. Usually, it applies to the areas adjacent to water bodies. It was established that under a humid climate, the storm runoff coefficient at unreclaimed sites is 2–3 times higher than at reclaimed ones [26]. Such results are possible when multilayered perennial plantings on suitable soils are created on the surface of a technogenic landscape.

Forestry reclamation is widespread in humid and subhumid areas. The high efficiency of this option largely depends on the eluvial processes in soils. However, because of the high substrate density, the survival rate of seedlings is low [53]. Moreover, some cereal plants may hamper the growth of woody plants [21]. Dissected topography minimizes these factors and increases the soil-ecological efficiency of forestry reclamation [55, 106]. It is also noted that areas covered with deciduous forests show faster litter transformation than coniferous forests [63]. In this way, the microbiocenosis similar to that in natural soils is formed [66]. The use of sea buckthorn (*Hippophae rhamnoides* L.) in reclamation contributes to nitrogen accumulation in the soils [107]. In some cases, the rates of soil nitrogen accumulation in sea-buckthorn plantations exceed those in areas with leguminous grasses [15].

Agricultural reclamation has the highest soil and ecological efficiency. The primary reason is that this reclamation option aims to form highly fertile soils. It is achieved through surface leveling, application of fertile substrates [38, 109], fertilizing [42], sowing crops [21], and maintaining the required fertility in the root layer [43, 71]. For this reason, agricultural reclamation is only appropriate for large areas [57]. Nevertheless, many references have described the use of crops in reclamation without radical soil improvement [20, 56, 78].

The review of research on reclamation has enabled us to identify some measures to increase the soil cover remediation efficiency (Fig. 3). First of all, we should assess the climatic conditions of the technogenic landscape location: the amount of precipitation, biologically active temperatures, evaporation rate, and other metrics. Then, the natural soils of adjacent areas should be studied to assess the zonal soil formation trends and identify the accompanying soil processes. The next step is to evaluate the quantity and quality of available FSL and PFS and classify technogenic substrates by their degree of suitability for soil formation. The reclamation options can be selected both for the entire technogenic landscape or specifically for its sections. Further, the substrates to be deposited on the surface and relief formation methods should be selected. Having evaluated all the above-listed conditions, we should select plant species for biological reclamation. At this step, it is important to take into account the ecological flexibility of plant species.

Sequence	Object assessment and development of recommendations		
1	Climatic conditions assessment		
2	Identification of zonal soil formation trends		
3	Assessment of locally available fertile and potentially fertile substrates		
4	Assessment of the man-made landscape rock properties		
5	Selection of the reclamation option		
6	Selection of the rocks to be deposited on the surface		
7	Selection of the surface relief formation method		
8	Selection of plant species for biological reclamation		
Stages of reclamation	Planning	Engineering	Biological

Fig. 3. The steps of technogenic landscape survey and recommendation development

The soil-ecological efficiency depends on the availability of resources and their use in due time. Obviously, all reclamation conditions and resources should be evaluated at the planning stage for maximum efficiency. A shortage of such resources as FSL and PFS at the engineering stage can significantly reduce the reclamation efficiency. At the biological stage, there are few chances to change the reclamation activities. Therefore, under a shortage of FSL and PFS, the artificial substrates should spatially and vertically alternate reasonably, and diverse relief formation methods should be used. It will contribute to a) the efficient use of the reclamation resources; b) the avoidance of “exotic” combinations of the soil-forming rock properties, climatic conditions, and plant species used at the biological stage; c) the increased biological diversity of a technogenic landscape.

Classification of soils in technogenic landscapes

Soil classifications in technogenic landscapes are just over two decades old, so they are based on the modern concepts of soil genesis. Before that, there was a long period of assessing the technogenic substrate suitability for growing crops and trees, or, conversely, selecting plants for industrial site greenspace expansion [109]. The result of the long efforts is the categorization of technogenic substrates into several classes by their potential fertility and phytotoxicity [11, 98, 110, 111]. Other research that was conducted before the creation of soil classifications for technogenic landscapes was technogenic landform grouping. Such grouping and rock classification can be found in several regulatory documents [112, 113]. In this paper, we will not dwell on these approaches. We only note that they served as the foundation for the classifications of the technogenic landscape soils.

Along with categorization according to the characteristics of substrate and relief features, it has been proposed to categorize technogenic landscapes by the degree of soil features preservation [114] and the structure of the newly formed soil profile [115]. The need to assess the diversity of phytocenosis formation conditions in disturbed areas has facilitated the development of landscape feature classifications. Taranov et al. [116] showed that various combinations of soil formation conditions within a single technogenic landscape could produce forest, sod-steppe, meadow, or bog evolution of young soils. Such a differentiation of conditions has become a foundation for classifying the soils of technogenic landscapes proposed by Eterevskoy et al. [117]. Besides the above attributes, the advantage of the proposed classification compared to the rock classifications widespread at that time is the use of soil properties that reflect elementary soil processes and the thickness of genetic horizons.

Nevertheless, these approaches were not further developed since, at that time, the surface substrates in disturbed areas were not considered to be soil or soil-like. The key reason for this attitude is the considerable predominance of rock features in the soils of technogenic landscapes and the weak development of classical soil horizons. However, despite the initial heterogeneity of technogenic substrates, most of them perform soil functions to provide living organisms with nutrition and moisture. In addition, the soils formed on such substrates eventually acquire features of zonal soils [118]. We consider that the listing of the Technosol into the World Reference Base for Soil Resources (WRB) was the tipping point in recognizing the surface substrates of technogenic landscapes as soils. From this moment, the modern classification of the soils of technogenic landscapes began.

WRB classifies not only formations with "traditional" soil attributes but also any substrates located within two meters from the surface and in contact with the atmosphere (except for ice and water bodies deeper than 2 meters). The classification principles are based on the measurable soil profile attributes. Their relations to soil-forming processes and the possible use of the soils are also taken into account. The key feature of Technosols is a significant amount (≥ 20%) of artifacts in the top layer 1 m thick and/or the presence of a low-permeability artificial geomembrane. The key qualifiers, specific to Technosols, include Ekranic, Urbic, Spolic, Garbic, stony and over-compacted soil qualifiers, Isolatic, Linic, Leptic, Hyperskeletic, and Subaquatic, Tidalic, Reductic, and Cryic only [119].

With its sufficiently broad interpretation of the soil concept and classification principles, allowing national classification systems to be fitted into, the WRB system has quickly gained popularity [100, 101, 120–123]. However, it should be noted that in most listed studies, the use of the WRB classification is limited to the use of the term Technosol without further subdivision into reference soil groups. Even fewer works assess technogenic landscape soils with additional qualifiers [39, 62, 120].

Another general substantive classification of the technogenic landscape soils is the Soil Taxonomy developed by the US Department of Agriculture [124]. In this classification, the soils of technogenic landscapes are not separated as an individual group. By their genetic properties, most of these soils are categorized as order Entisols: young soils without morphologically distinct horizons [49, 65, 125]. The suborders are divided by soil moistening and thermal conditions. By mineral component properties, stony soils of technogenic landscapes are categorized within the suborder of Orthents. In contrast, sandy soils belong to the suborder of Psamments. The suborders are divided into great groups based mainly on temperature and water regime characteristics. Thus, stony soils of technogenic landscapes in areas with precipitation equally distributed throughout the year (udic moisture regime) belong to the suborder of Udorthernts [43, 46, 113, 126]. In the areas with a temporarily dry climate (ustic moisture regime), these soils should be classified as Ustorthents. Special attention to the anthropogenic influence on soil formation is paid at the subgroup level. Among other subgroups, there are subgroups diagnosed by the presence of human-altered or human-transported materials in soil profiles. The soils of technogenic landscapes mainly belong to the subgroups of Anthrodensic soils (soils with a dense contact due to mechanical compaction, e.g., compacted mine spoil) and Anthroportic soils (soils having 50 cm or more of human-transported material in their profile). However, the Typic subgroup is more often used to describe such soils [43, 113]. The soils of technogenic landscapes with better-developed genetic horizons can be classified as the order of Inceptisols [49]. More detail is added at the level of soil families (within subgroups), where classes for human-altered and human-transported are specified: Methanogenic, Asphaltic, Concretic, Gypsifactic, Combustic, Pyrocarbonic, etc. Local soil characteristics can be reflected at the series level. Finally, landscape features (slope steepness, slope exposure, the presence of new material in surface cover, etc.) are taken into account at the lower level of taxonomy (soil phase), which is essential for the soil classification and practical use [124]. Although Soil Taxonomy is a very complex and practically oriented classification system, it is not used much when dealing with the soils of technogenic landscapes in the United States. Often, other terms are used, e.g., minesoils [37, 43].

The groupings of human-transformed soils and some other national soil classifications [5, 126–129] are also based on substantive principles. The new Russian soil classification system (RSC) also belongs to substantive-genetic classification systems [130]. According to its principles, formations with "rudiments" (morphologically unexpressed genetic horizons) cannot be diagnosed as soils because they do not have sufficiently conservative features. It is proposed to call them "technogenic surface formations" (TSF) and, unlike soils, divide them not into classes, types, and subtypes, but groups and subgroups. Such groups are distinguished by formation conditions and potential suitability for further use. For instance, Quasizems are TSFs, in which the surface is composed of humified substrates. Naturfabricants are TSFs devoid of a humus layer and formed of mineral, organic, or organomineral materials. Artifabricants include TSFs composed of filled artificial material of various origins (household, industrial, and agricultural waste). An advantage of the RSC is separating a specific group of Toxifabricants TSFs composed of toxic substrates. Unfortunately, more detailed diagnostics taking into account the nature and degree of toxicity is not developed yet. The criteria for distinguishing TSF subgroups are material composition and occurrence.

Technogenic formations with poorly developed genetic horizons (W: weakly developed humus layer and/or O: litter and peat layer) are categorized as the initial soil formation trunk, poorly developed soil order [131]. Depending on the soil-forming rock composition, poorly developed soils are divided into petrozems, psammozems, and pelozems with further specification into humic, calcareous, and gypsiferous soils (e.g., types petrozems, humus (protohumus) petrozems, carbopetrozems, and gypsum petrozems). The fundamental division into TSF and poorly developed soils, and the unique features of their functioning in technogenic landscapes, make the diagnostics and soil/non-soil identification quite challenging [80]. Still, the RSC is often widely used in the Russian academic literature on disturbed areas [75, 84, 132, 133].

The classification of the technogenic landscape soils developed by the Institute for Soil Science and Agrochemistry (ISSA), Siberian Branch, Russian Academy of Science [34, 104, 134–136] offers a more detailed differentiation of surface formations at the rock-soil interface. This classification is generally applied in Russian academic literature. According to the principles of this classification, just like in the WRB, any surface substrate in contact with the atmosphere is categorized as soil [137]. In the ISSA classification, the technogenic landscape soils are categorized not as TSF and not as initial soils (like in the RSC) but as the post-lithogenic soil formation trunk. Instead of orders, this system has classes (branches) distinguished by the lithoreflectivity of soil-forming rocks. Embryozem soils are categorized as biogenically undeveloped soils. Embryozems are formed on clay, loamy and sandy substrates and easily weathered stony sedimentary rocks. The lithogenically undeveloped soils class includes Eluviozems. They are developed on coarse-clastic massively crystalline and strongly metamorphosed sedimentary rocks. The Technozem class includes the soils with artificially formed horizons. According to the number of artificial horizons, Technozems are divided into differentiated and nondifferentiated types.

Embryozems and Eluviozems are divided into types by the soil features governed by the plant community development. Initial, organic-accumulative, sod, humus-accumulative, and dry peat types are distinguished, and their gleyic analogs for the Embryozem class are identified. In the first versions of the classification [67, 137], the Embryozem subtypes were distinguished by the processes accompanying the primary type-diagnostic processes (e.g., typical, leached, podzolic). However, with the broader geographic coverage of the technogenic landscape studies and factual basis, the approaches to subtype differentiation have changed. Therefore, in the latest ISSA classification editions [138], the properties of the type-diagnostic horizons reflecting the conditions of soil formation are used as the subtype criteria. Along with typical subtypes, the cryptopedogenic subtype is distinguished in initial embryozems. Felty, litter, and peat subtypes are distinguished in organic-accumulative soils. Xerophytic and hygrophytic are distinguished in sod soils, and the coarse humus-accumulative subtype is distinguished in humus-accumulative soils.

With such approaches to the soils grouping, the ISSA soil classification is more functional-genetic than substantive. Therefore, this classification significantly simplifies the mapping of technogenic landscapes and facilitates the quantitative assessment of their soil-ecological state [4, 105, 139], particularly using remote sensing methods [140].

Despite the different approaches to soil diagnostics in the above classifications, we tried to correlate the major taxa by the features representing soil conditions and young soil formation trends (Table 2). Table 2 shows that the features based on the soil-forming rock properties are sufficiently represented in all classifications. The same applies to the constructed soils with artificially created horizons. The exception is technogenic landscapes composed of toxic rocks. In some classifications (RSC and the Soil Taxonomy), such substrates are not considered soils because they do not fulfill one of the main functions: enabling growth and development of plant communities. However, the rock toxicity to specific plant species may be different. Therefore, in our opinion, they should be classified as soils. In the WRB, the soil toxicity is accounted for by the Toxic additional qualifier. In the ISSA classification, the soils formed on toxic rocks and the soils not featuring organogenic horizons yet are identified as initial Embryozems and Eluviozems.

The effects of elementary soil processes, despite their weak performance in technogenic landscapes, can be assessed using natural soil features. For the soils of technogenic landscapes, the most suitable features for such assessment are the accumulation of organic matter: humus, litter, and peat accumulation. In addition, the organogenic horizon features in the sites with climax vegetation communities enable us to identify the soil formation trends [138].

Evaluating the suitability of the considered classification approach for the technogenic landscape soils, we can conclude that all of them are applicable for adequate assessment of these soils. However, the literature review indicates low demand for such classifications. In the studies where modern classifications are referred, soil diagnostics are limited to top-order taxa only. We suppose that the main reason is the relatively short period of special studies of these soils. Secondly, most classifications rely mainly on inherited rock features, making it difficult to consider the spatial heterogeneity of technogenic landscapes.

Table 2

Key technogenic landscape soil taxa used in most common classification systems

Features/ processes	Classification			
	RSC (2004, 2008)	WRB (2015)	Soil Taxonomy (2014)	ISSA Soil Classification (2010, 2020)
Soil-forming rocks				
Dense	Naturfabricats and Toxifabricants: (toxi-) abralites, (toxi-) lithostrates (carbo-, gypsum-) petrozems and (carbo-, gypsum-) humus petrozems	Technosol: Ekranic, Urbic, Spolic, Linic, Leptic, Hyperskeletic	Entisols: Orthents, Udorthents, and Ustorthents All Inceptisols	All Eluviozems and Embryozems
Loose	All Naturfabricants, Artifabricants, and Toxifabricants Pelozems and Psammozems, humus Pelozems and Psammozems	Technosol: Urbic, Spolic, Garbic, Reductic, Cryic	Entisols: Psamments, Fluvents All Inceptisols	All Embryozems
Toxic	All Toxifabricants	Technosol with toxic horizons	N/A*	Initial Eluviozems and Embryozems
Constructed soils	Quasizems: Replantozems and Urbiquasizems	Technosol: Isolatic, Linic, with Transportic features	Entisols: Fluvents	Differentiated and undifferentiated Technozems
Organic accumulation features				
Litter accumulation	Pelozems, Psammozems, (carbo-, gypsum-) Petrozems	All Technosol with Folic and Protofolic horizons	Inceptisols: Gelepts, Cryepts, Udepts, Ustepts	Organic-accumulative and sod Embryozems and Eluviozems
Humus accumulation	Humus Pelozems and Psammozems (carbo-, gypsum-) Petrozems	All Technosol with Humic, Molic, Umbric horizons	Inceptisols: Cyepts, Udepts, Ustepts, Xerepts	Sod and humus-accumulative embryozems
Peat accumulation	Pelozems, Psammozems, (carbo-, gypsum-) Petrozems	Technosol with Histic horizons	Inceptisols: Aquepts, Gelepts, Cryepts, Udepts	Organic-accumulative peat Embryozems and dry peat Eluviozems

Note. N/A: no data available.

Conclusion

The literature review indicates that, at present, the soils of technogenic landscapes are of scientific interest globally. An essential part of the studies is local and aimed at analyzing the soil features of individual technogenic sites. However, the geographic coverage of soil studies in technogenic landscapes has expanded in recent years. With their short lifespan and specific formation factors, the soils of technogenic landscapes are not in equilibrium with the environment. Therefore, their key feature is dynamic transformation. Trends of soil-forming processes in technogenic landscapes do not always follow the zonal features. The formation trends of zonal and technogenic soil coincide if artificial substrates have properties close to soil-forming rocks in undisturbed soils. Along with soil-forming rock properties, young soils are often formed by organic matter accumulation processes. In various conditions, it could be humus, litter, and peat accumulation. High humus accumulation rates in the soils of technogenic landscapes are detected not only in moderate climate areas but also in a hotter and more humid climate. This is possible on rocks enriched with fine particles or capable of releasing them through weathering. The high density of technogenic substrates and their shrinkage negatively affect soil formation. The surface of most technogenic landscapes is highly differentiated by relief, density, composition, and some other soil-forming rock properties. In such conditions, the development of soils and topsoil is diversified, while the divergence of soil geochemical processes in time and space contributes to the further isolation of evolutionary trends, which are often opposite.

The soil formation efficiency in technogenic landscapes is primarily determined by the efficiency of reclamation activities, which depends on the availability of resources and their use in due time. The maximum efficiency is achieved if all the conditions and resources for reclamation are evaluated at the planning stage. At the engineering and, even more so, at the subsequent biological stage, there are few opportunities to improve the reclamation efficiency. Therefore, under a shortage of FSL and PFS, the artificial substrates should spatially and vertically alternate reasonably, and diverse relief formation methods should be used. It is necessary to: a) efficiently use reclamation resources; b) avoid "exotic" combinations of soil-forming rock properties, climatic conditions, and plant species used at the biological stage; c) increase the biological diversity of technogenic landscape.

Modern soil classifications are sufficient for evaluating the properties and features of the soil formation in technogenic landscapes. At the same time, the literature review indicates low demand for such classifications. In the works where modern classifications are referred, soil diagnostics are limited to top-order taxa only. This fact, as well as individual features of each technogenic landscape and the lack of appropriate generalization, negatively affect the development of the functioning and reclamation concepts of technogenic landscapes. The development of the methods and approaches to assessing their soil-ecological state also gets complicated, as well as the design and improvement of reclamation technologies. We believe that our analysis of the soil properties, classifications, and approaches to reclamation will contribute to a better understanding of technogenic landscape functioning and their efficient use, and will promote further research on the concepts of the soil formation in technogenic landscapes.

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Author info:
Sokolov Denis A, Dr. Sci. (Biol.), Leading Researcher, Laboratory of Soil Reclamation, Institute of Soil Science and Agrochemistry, Siberian Branch of the Russian Academy of Sciences, 8/2 Academician Lavrentiev Av., Novosibirsk 630090, Russian Federation.
ORCID iD: http://orcid.org/0000-0002-7859-7244
E-mail: sokolovdenis@issa-siberia.ru
Androkhanov Vladimir A, Dr. Sci. (Biol.), Director of the Institute of Soil Science and Agrochemistry, Siberian Branch of the Russian Academy of Sciences, 8/2 Academician Lavrentiev Av., Novosibirsk 630090, Russian Federation.
ORCID iD: http://orcid.org/0000-0002-2123-2367
E-mail: androhanov@issa-siberia.ru
Abakumov Evgeny V, Dr. Sci. (Biol.), Professor, Department of Applied Ecology, Saint Petersburg State University,13B Universitetskaya Emb., St. Petersburg 199034, Russian Federation.
ORCID iD: http://orcid.org/0000-0002-5248-9018
E-mail: e_abakumov@mail.ru

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