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APPLIED PROBLEMS
OF ARID LANDS DEVELOPMENT

Transformation of the Soil–Vegetation Cover in Carrier Rocket First-Stage Impact Areas

P. P. Krechetov[a], V. V. Neronov*[b], T. V. Koroleva[a], and O. V. Chernistova[a]

[a] *Faculty of Geography, Moscow State University, GSP-1, Leninskie Gory 1, Moscow, 119991 Russia*
[b] *Severtsov Institute of Problems of Ecology, Russian Academy of Sciences, Leninskii pr. 33, Moscow, 119071 Russia*
**e-mail: vneronov@mail.ru*

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Abstract—At carrier rocket first-stage impact areas in desert landscapes of central Kazakhstan, we evaluate the mechanical transformation of the soil–vegetation cover. We establish that for soil restoration and revegetation, a time period of no less that 15–20 years is necessary, which can be shortened if recultivation measures adapted to desert ecosystems are put into effect.

Keywords: space rocket activity, technogenic factors, transformation, soils, vegetation, desert ecosytems.

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The main forms of environmental impact of space rocket activity (SRA) are mechanical damage to the soil–vegetation cover in impact areas of carrier rockets (CR) modules and chemical pollution of ecosystem components in launch-complex areas and spent-stage impact areas (Krechetov et al., 2008). Priority attention in making SRA environmentally safe is focused on chemical pollution of the environment, since, in particular, a highly toxic substance is used as rocket fuel: uns-dimethylhydrazine (Koroleva, 1995; Kasimov et al., 2006). Multiyear observations by Moscow State University's Faculty of Geography—at the order of the Russian Federal Space Agency (Roskosmos)—in CR module impact areas located in various phytomes have established that the areas of mechanical damage to ecosystems substantially exceed areas of chemical pollution.

CR module impact regions are usually ellipses several hundred to thousands of square kilometers in area. These territories can be zones of increased ecological risk. The most intensively mechanical disturbances to natural ecosystems are manifested in CR first-stage impact regions, the separation of which occurs at altitudes above 60–90 km. The momentum of a stage upon entering dense atmospheric layers is insufficient for destruction, which can occur as a result of aerodynamic overload or as a result of explosion when tanks with fuel residues explode from overheating. Complete destruction of first-stage metal structures, which can weigh 20–30 t, occurs upon impact with the ground, as a result of which a crater 1 m in depth and up to 10 m in diameter forms at the impact site depending on the character of the ground surface. During the impact of the first stages of Proton CRs, which use uns-dimethylhydrazine as fuel, an explosion of fuel residues occurs, as a result of which structure fragments scatter in a radius of 100–120 m from the epicenter. The first stages of Soyuz CRs, which use hydrocarbon fuel (kerosene), impact without explosion, and in this case the metal structure fragments of the stage after ground impact are scattered compactly (Kondrat'ev et al., 2007).

OBJECTS AND METHODS OF STUDY AND WORK AREA

To quantitatively evaluate the mechanical impact to the soil–vegetation cover in Proton CR first-stage impact areas launched from the Baikonur cosmodrome, the authors conducted field studies of the state of soils and aboveground phytocenoses in one of central Kazakhstan's impact regions. The study territory is characterized by high technogenic load: up to 11 impacts annually. Studies were conducted in six regions with various impact periods (1999, 2000, 2002, 2004, 2005, 2006). Mechanical transformation of soils was determined by the degree of disturbance in constructing the soil profile (the absence or decrease in the depth of the humus horizon, technogenic turbo-jet pollution) and by the change in soil density. To evaluate the state of aboveground phytocenoses, we used the technique of geobotanical descriptions of standard plots (Voronov, 1973). Their size for desert vegetation was 100 m^2 (10 × 10 m). As indices of the state of vegetation communities, we used such characteristics as species diversity, the total projective cover, the average height of the grass–shrub cover, aboveground phytomass reserves, and certain structural and population characteristics.

The study regions were located in the southwest outskirts of the Kazakh Upland and the borders of the

Table 1. Areas of mechanical disturbances in soil cover in Proton CR first-stage impact areas

Impact area, date	Crater depth, cm	Crater area, m^2	Total area of mechanical disturbances, m^2
Zharkuduk River floodplain, June 2002 (T. 1)	100	79	3230
	30–50	39	
Seasonal waterway, June 2000 (T. 2)	30–70	50	100
Zhide sai floodplain, March 2004 (T. 3)	70	79	393
	30	16	
Watershed slope largely filled with rubble, December 2005 (T. 4)	30–50	45	67.5
Dealluvial slope of rocky outlier, crate virtually swallowed up, 1990 (T. 5)	0	16	79
Slope of rocky outlier, June 2006 (T. 6)	30–40	39	59
Mean value	46	61	655
Mean value (exluding T. 1)	38	49	140

Turan lowland (Republic of Kazakhstan). The soil cover was zonal brown desert–steppe soils together with brown alkaline and saline desert soils. Valleys of seasonal waterways (sais), hollows, and river terraces were occupied by saline and alkali soils. Depending on the level of groundwater occurrence in depressions, poic soil combinations form.

The region's vegetation cover is predominated by desert vegetation communities of the northern desert subzone with desert–steppe species of the Gramineae family (Botanicheskaya..., 2003). The vegetation cover in vast regions are characterized by complexity and a mosaical structure. In the independent upland landscapes with brown desert–steppe soils, complexes of *Salsola arbusciliformis*, *Artemisia terrae-albae*, *Stipa richteriana*, and *S. kirghisorum* communities have developed. On salinized soils of subordinate landscapes, Egnatioides in combination with long-standing Russian thistle (*Anabasis salsa*, *Nanophyton erinaceum*, *Halocnemum strobilaceum*) and other salinity-resistant long-standing dwarf semishrubs (*Atriplex cana*, etc.) play the dominant role.

RESULTS AND DISCUSSION

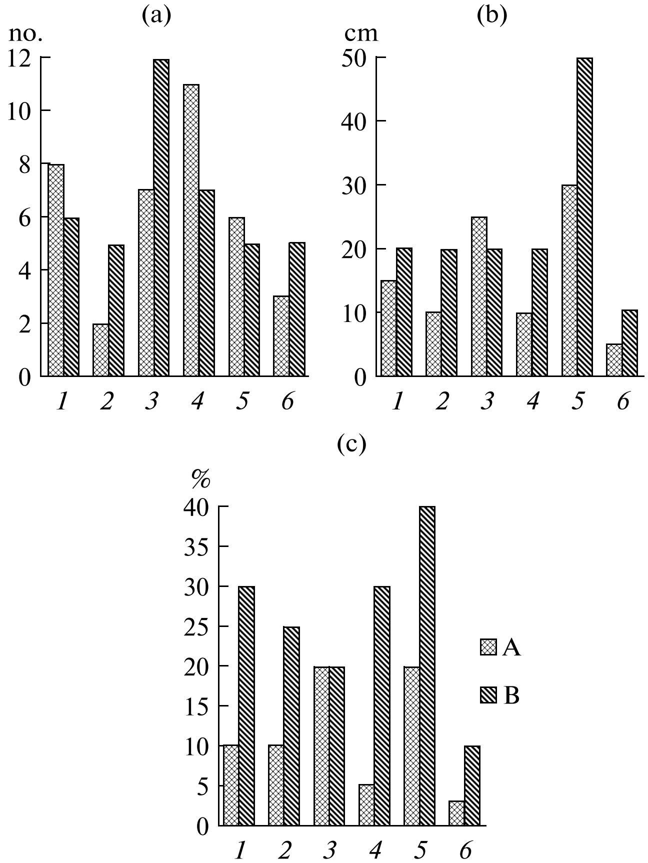
Transformation of the soil cover. In studying damage to the soil cover, it was established that the main disturbance was noted in propulsion unit impact areas. When a propulsion unit impacts with the ground, a crater forms up to 10 m in diameter with an area of 40–80 m^2 (Table 1). The decrease in the depth of the soil profile (A + B) exceeds 75% of background values. In the vicinity of the crater, a zone 0.5–1 m wide forms backfilled with the scant horizon buried under the humic horizon or soil-generating feed rock. The depth of technogenic sediment varies from 5 to 20 cm.

During efforts to clear the territory of the impact area of a stage's structural fragments, cargo vehicle transport exerts an intense effect on the soil cover. In conducting these jobs in the moist period at impact areas located on friable sedimentary rocks, deep automobile tracks form. Their area can reach from 300 m^2 to more than 3000 m^2. In the case of a stage impacting on rocky areas and dense rocks, the disturbance areas are limited to the crater and the ring of lower lying rocks around it, with an area no greater than 100 m^2 (Table 1).

As a result of impact of a rocket stage and its further evacuation, soil compaction has been noted. Our investigations revealed differences in the physical properties of soils in and outside impact areas. The largest variability in soil density was noted in an impact area in the valley of a seasonal waterway (Table 2). The soil cover here is meadow saline-alakine and saline soil on thinly sorted saline alluvial loam. The near groundwater table results in high moisture of the soil profile. During physical impact on such soils, intense compaction of the humic horizon occurs. Analysis of the data obtained has revealed maximum compaction in saline soil located immediately in the zone of technogenic influence (the edge of the crater)—up to 1.3–1.4 kg/dm^3. In saline-alkaline soils in the background area, the density of the humic horizon changes from 0.9 to 1.2 kg/dm^3. From a depth of 20–30 cm, the

Table 2. Changes in soil densities in Proton CR first-stage impact areas

Profile	Depth, cm	Density				
		Mean	Minimum	Maximum	Standard deviation	Variation coefficient
Meadow saline-alkaline and saline, Zhakuduk River floodplain, June 2002 (T. 1)						
Impact area	0–5	1.31	1.22	1.40	0.09	6.94
	5–10	1.45	1.37	1.55	0.10	6.55
	10–20	1.33	1.30	1.34	0.02	1.88
	20–30	1.50	1.44	1.58	0.08	5.06
	30–40	1.49	1.46	1.50	0.02	1.26
	40–50	1.42	1.41	1.44	0.01	0.81
Background	0–5	1.22	1.10	1.29	0.10	8.20
	5–10	1.30	1.28	1.31	0.01	0.94
	10–20	1.51	1.49	1.52	0.02	1.12
	20–30	1.51	1.43	1.56	0.08	5.03
	30–40	1.48	1.40	1.57	0.09	5.98
	40–50	1.55	1.50	1.61	0.06	3.65
Meadow saline-alkaline and alkaline, floodplain of seasonal waterway, June 2000 (T. 2)						
Impact area	0–5	1.22	1.15	1.28	0.07	5.59
	5–10	1.35	1.26	1.41	0.08	5.79
	10–20	1.60	1.55	1.66	0.06	3.49
	20–30	1.76	1.71	1.79	0.04	2.25
	30–40	1.63	1.61	1.65	0.02	1.26
Background	0–5	1.16	1.10	1.22	0.06	5.36
	5–10	1.22	1.18	1.26	0.04	3.42
	10–20	1.63	1.54	1.69	0.09	5.26
	20–30	1.63	1.53	1.71	0.09	5.68
	30–40	1.65	1.54	1.73	0.10	5.98
Brown desert–steppe sandy, Zhide sai, March 2004 (T. 3)						
Impact area	0–5	1.45	1.35	1.51	0.09	6.10
	5–10	1.72	1.61	1.78	0.09	5.23
	10–20	1.65	1.49	1.75	0.14	8.29
	20–30	1.50	1.43	1.59	0.08	5.34
	30–40	1.34	1.19	1.47	0.14	10.59
Background	0–5	1.54	1.51	1.58	0.04	2.65
	5–10	1.41	1.38	1.44	0.03	2.10
	10–20	1.45	1.44	1.45	0.01	0.37
	20–30	1.44	1.35	1.52	0.09	6.01
	30–40	1.57	1.51	1.66	0.08	5.09
Brown desert–steppe alkaline and saline underdeveloped, watershed slope largely filled with rubble, December 2005 (T. 4)						
Impact area	0–5	1.35	1.29	1.39	0.06	4.34
	5–10	1.57	1.52	1.60	0.04	2.87
	10–20	1.55	1.51	1.58	0.03	2.18
	20–30	1.61	1.59	1.63	0.02	1.22
	30–40	1.54	1.52	1.57	0.03	1.69
Background	0–5	1.46	1.43	1.53	0.06	3.97
	5–10	1.55	1.53	1.57	0.02	1.23
	10–20	1.63	1.54	1.68	0.08	4.82
	20–30	1.59	1.53	1.66	0.07	4.16
	30–40	1.57	1.55	1.58	0.01	0.86
Brown desert–steppe alkaline and saline underdeveloped, dealluvial slope of rocky outlier, crater virtually swallowed up, 1990 (T. 5)						
Impact area	0–5	1.22	1.17	1.30	0.07	6.05
	5–10	1.20	1.15	1.28	0.07	5.72
	10–20	1.18	1.11	1.21	0.06	4.86
	20–30	1.34	1.31	1.36	0.02	1.79
	30–40	1.29	1.27	1.30	0.02	1.16
Background	0–5	1.23	1.21	1.26	0.03	2.53
	5–10	1.16	1.12	1.20	0.04	3.33
	10–20	1.34	1.27	1.46	0.10	7.72
	20–30	1.34	1.28	1.40	0.06	4.53
	30–40	1.38	1.35	1.39	0.02	1.77



Indices of the state of phytocenoses in impact areas and in adjacent background areas: (a) species diversity (number of species per 100 m^2); (b) mean plant height (cm); (c) overall projective plant cover (%). A, disturbed sites. B, adjacent background sites. *1–6*, sample site numbers.

background values of soil density reliably do not differ from the technogenically transformed soil (Table 2).

Similar regular patterns have also been observed in other impact areas located on friable sedimentary rocks. Thus, in an impact area located in a sai, a tendency toward an increase in the mean density values for humic soils horizons (0–10 cm) has been noted. As well, in the background area, the density was 1.16–1.22 kg/dm^3, whereas in the technogenically transformed area, it was 1.22–1.35 kg/dm^3 (Table 2).

The increase in soil compaction in the technogenically transformed area has also been noticed on brown desert–steppe sandy soils. If for the 0–5 cm layer the differences are not reliable, then for depths of 5–10, 10–20, and 20–30 cm, they are already substantial. For instance, the densities of these horizons for the background soil are 1.4–1.5 kg/dm^3 and for the technogenically transformed soil, they are 1.5–1.7 kg/dm^3.

For brown desert–steppe saline and alkaline underdeveloped soils formed on rubbly dealluvial deposits, no differences in the background and technogenically transformed soils have been established (Table 2).

It is noteworthy that the increase in soil density in CR first-stage impact areas has a local character and pertains to areas of maximum technogenic impact (propulsion unit impact areas) on soils formed on sandy and loamy deposits. First-stage impacts on rocky and rubbly soils and rocks do not cause compaction; they only lead to mechanical destruction of the soil profile in the crater area.

Transformation of the vegetation cover. At the level of vegetation communities, the degree of disturbance in the first-stage impact region is characterized by a gradual increase in synatropization of the floristic composition with intensification of technogenic action and local changes in the spatial population and phytocenosis structures (Neronov, 2007). Transformation of the natural vegetation cover is connected with the formation of pioneer groupings in mechanically distrubed CR first-stage impact areas. In the long term, revegetation is the result of microfocal demutative vegetational fluctuations (Korshunova and Trofimova, 2000).

Vegetation reacts more sharply to pulse impact-thermal action in the explosion and destruction of a CR stage, leading to complete or partial death of phytocenoses in a radius of 50–150 m from the center of the crater depending on the local relief. Wider disturbances in the vegetation cover can be related to the spreading of explosion-related technogenic fires and combustion of aboveground parts of phytocenoses over significant areas (when the fire is not extinguished in a timely manner). In addition to simple mechanical or pyrogenic impacts, desert phytocenoses also experience a certain chemical impact that, however, manifests itself only locally and does not lead to substantial changes in communities.

As integral characteristics of a phytocenosis, which characterize it as an entire system, we can examine the indices of the overall projective cover (%), the mean height of the grass–shrub cover (cm), and the level of species diversity (figure).

As is seen from the figure, the studied communities differ quite noticeably in their indices. Thus, nowhere was the overall projective cover high on the whole, and it varied within the limits of 3–40%. These were the background values for desert vegetation communities in various edaphic conditions (Botanicheskaya..., 2003). It should also be noted that in nearly all cases, the projective cover of disturbed areas, in contrast to the background values, was lower. This is related to the destruction of long-standing dwarf shrubs and an increase in the degree of rarity in phytocenoses. Values similar to the norm were also fixed over the average height of the grass canopy (varying in the limits of 5–50 cm). On average, the height of the grass canopy in background areas was also higher than in disturbed areas. Species diversity was everywhere relatively low and changed from 2 to 12 species within the limits of a plot of 100 m^2. The communities that were the richest in species composition and the most closed were restrictively linked to the sandy–loamy differences in soil, which were charazterized by a more favorable moisture regime. In contrast, communities of loamy differences, especially with a high content of low-soluble salts, are characterized by significant rarity and poor species composition. In a number of cases, impoverishment of species composition is related to technogenic disturbance, whereas in others, the opposite picture is observed. Owing to the invasion of weeds and annual explerents into a disturbed community, species diversity here can noticeably increase and be significantly higher than in background areas. Similar species in a "cenophobe" state, in conditions of technogenic impact, are actively introduced in combined seral systems and form a particular group, which have received the picturesque name of "gray biota" (Shvartz, 2004). In this connection, in interpreting the indicative role of floristic diversity, it is necessary to take into account the structure of the floristic list (the ratio of plant lifeforms, ecological-phytogenitic groups, the spectrum of ecological-cenotic strategies, etc.).

Comparative analysis of the state of cenopopulations of the background lifeforms of desert communities has shown that the leading role in them is played by long-standing dwarf shrubs, which represent a zonal lifeform of desert vegetation. The high density of their cenopopulations (from 8.6 to 23.0 specimens/m^2), as well as the full-grown age composition (the presence of the entire spectrum of ages in the complete lifecycle) in background areas testifies to the absence of deviations in the normal development of natural communities and their stable state. In contrast, in all disturbed areas, the density of dwarf shrubs was noticeably lower (down to their complete absence).

This is evidence of the high sensitivity of dwarf shrubs to thermal and mechanical impact, as well as of the relatively slow rate of their restoration and formation of normal cenopopulations, which makes it possible to consider dwarf shrubs as good indices of the state of vegetation communities in CR first-stage impact areas.

Changes in the density of other widespread plant lifeforms—permanent cereals—better reflect the specificity of edaphic conditions of the formation of communities and do not always characterize the degree of disturbance of the vegetation cover.

Yet another reliable index of the degree of technogenic impact on vegetation communities is the reserve of the aboveground phytomass. Data obtained during evaluation in plots (2.5 × 2.5 m) in the first-stage impact areas made it possible to establish that, despite the significant fluctuations in this index for background communities (depending on the type of community, the values changed within the limits of 162–262 g/m^2), in all cases, its level in disturbed areas was significantly lower (sometimes up to 13 times). Since desert phytocenoses are characterized by quite high interannual variability depending on the meteorological conditions of a specific year, to evaluate the degree of variability of the obtained values of aboveground phytomass reserves, further studies are necessary.

CONCLUSIONS

Our field observations have shown that mechanical disturbances in impact areas have a local character and the fraction of areas subjected to physical degradation during the entire time of a territory's use was, in the most unfavorable estimates, no greater than 0.5% of the entire area of the impact region. With time the soil cover is restored and the area of degraded soils decreases. Recultivation works during which the surface was leveled foster an increase in the restoration rate of the soil cover.

For full restoration of the soil–vegetation cover in impact areas, depending on the lithological–edaphic conditions, in all probability a period of no less than 15–20 years is required. The vegetation cover experiences local technogenic impact and, on the whole, for the impact region of spent first stages, is characterized by the background state in the absence of visual disturbances in the floristic composition, the spatial and horizon structure, and biological productivity indices.

In the interest of preventing additional negative impact to the soil–vegetation cover of the territory, it is necessary to introduce a series of ecological restrictions into the regulations on searching for fallen stages and their long-term use, in particular, restrictions on the movement of equipment off of existing roads and an increase in the degree of cleanup of small debris from stages in impact areas. To speed up restoration processes of the vegetation cover in CR first-stage impact areas, it is expedient to develop recultivation measures adapted to given physical–geographical conditions (for instance, introduction of plant seeds of the first stages of restorative vegetative fluctuation, etc.).

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