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Resources of Organic Carbon in the Soils of Tundra and Forest-Tundra Ecosystems in Russia

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Abstract—An original database on soil descriptions performed in Russia was analyzed. For different tundra landscapes, the average carbon resources were estimated, and characteristics of their geographical distributions were studied. Absolute carbon values in the tundra zone and its regions were calculated. The results obtained were compared with relevant published data on Russian and world tundra zones. The total amounts of carbon in the phytomass, phytodetritus, and soil of Russian tundra areas were compared.

Global climatic changes are now being broadly discussed by both the scientific community and the general public. Arctic ecosystems are generally believed to be the most sensitive to climatic changes; in turn, these ecosystems may affect climatic changes (Billings *et al.*, 1982). These relationships largely occur through the biogenic cycle, which is best reflected in the carbon cycle. Therefore, it is important to perform comprehensive estimations of carbon resources in the Arctic and Subarctic, including estimations of carbon resources and flows in various components of natural systems.

According to different estimations, the total area of the tundra is about 8% of the total area of all terrestrial ecosystems. Nevertheless, the total size of the two main carbon pools (in the soil and in the phytomass) in the tundra is greater than in most other biomes. Tundra soils contain 13.7% (191.8×10^{12} out of 1395.3×10^{12} kg) of the total carbon accumulated in soils (Ajtay *et al.*, 1979). Note, however, that different authors report different estimates of the world and regional carbon resources and their distribution among zonal ecosystems. Many of the published estimates either are expert estimates or have been obtained via simple extrapolation of a limited amount of field data to large areas without taking into account the soil mosaic. Comparison and collation of independent estimates with one another is often difficult. Therefore, researchers usually use various bases for geographical generalizations, e.g., soil or vegetation maps, general schemes, and reference materials.

The purpose of this study was to reestimate both the average and total carbon content in soils of the Russian tundra zone, taking into account the natural heterogeneity of the distribution of the organic matter of the soil. This study is a part of a program studying the carbon cycle in the Russian Arctic. Earlier, the contents of carbon in the phytomass (Karelin *et al.*, 1995) and its biogenic flows (Zamolodchikov *et al.*, in press) were estimated in the framework of this program. In all of these studies, the same geographical base was used (Isachenko *et al.*, 1988), which makes it possible to obtain unified characteristics of the carbon cycle in both the entire Russian tundra zone and in individual subzones and regions.

MATERIALS AND METHODS

In the Russian scientific literature, the term soil organic matter has several meanings. In this study, we used the term in the broad sense, only excluding from the soil organic matter the living organic matter and half-decayed remnants that retain any structure. The data were obtained from an original database on soil descriptions performed in Russia. From the data set, we selected 260 soil profiles obtained in the tundra zone.

For each profile, we calculated the organic-matter content from the data on the volume weight, percentage of the organic matter, and the depth of each horizon (including the A0 horizon); the results for each horizon were then totalled. If the data on the percentage of organic matter were not available for some horizons in the profile, we approximated them based on the data on adjacent horizons or on similar profiles.

The absence of data on volume weight for a considerable portion of the profiles studied hindered the calculations. To overcome this difficulty, we selected profile data in which the volume weight had been determined in all horizons and arranged the data according to geographical subzones, vegetation types, and soil types. Based on the averaged values obtained, we calculated the missing values of volume weight in the remaining profiles, accurate to one decimal place.

We calculated the contents of organic matter in both the upper horizons that might be considered the A0 horizon (litter) and in the peaty horizons of podzolic boggy soils. The organic-matter content was calculated for the entire soil layer described in the corresponding

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source. The depth of the soil layers varied from 20 to 100 cm, depending on the zonal and subzonal types of tundra soils. We excluded profiles with a depth of less than 20 cm and those containing organic matter in only one or two horizons from calculations. To estimate the carbon resources, we assumed 1 kg of the soil organic matter to be equivalent to 0.57 kg of carbon (Kobak, 1988).

A computer map of Russian tundra landscapes (Karelin *et al.*, 1995) constructed based on the landscape map by Isachenko *et al.* (1988) with a scale of 1 : 4000000 that served as the basis for geographical generalizations. For calculation of areas and processing and output of images, we used the IDRISI 4.0 cartographic software package. The electronic map allowed us to estimate the areas of individual landscapes, regions, and the entire biome studied. Landscape ecosystems within individual regions were considered to be elementary areas. We distinguished between zonal ecosystems (Arctic deserts; Arctic, typical, and southern tundras; and forest-tundra), mountain ecosystems (deserts and tundras), and, within them, hydromorphic intrazonal ecosystems (bogs and river floodplains). In total, 80 elementary areas were distinguished.

Points with known amounts of soil organic-matter content were compared with the elementary areas according to their geographical coordinates and landscape descriptions. Afterwards, we calculated mean values from all data for the same elementary area. The standard error of the mean for the elementary areas was calculated as the ratio of the mean-squared deviation to the square root of the number of values compared with the given elementary area.

For many elementary areas, there were too few (one or two), if any, original values. In this case, we pooled the elementary areas over regions or (rarely) subzones. For example, the average values for typical tundras of the Eastern European province and the Polar Urals and for river floodplains in all typical and southern tundras of Russia were obtained by this method.

The total organic-matter content in the elementary area was calculated as the corresponding mean value multiplied by the area. Summarizing these values, we calculated the total soil-carbon contents in the region or the entire zone. The regional and zonal average values were calculated as the total content divided by the corresponding area. The standard errors of the total and average regional values were calculated in the same way as for the elementary areas.

RESULTS AND DISCUSSION

Table 1 shows the average and total amounts of soil organic carbon for various landscapes in different regions of the Russian tundra zone, forest-tundra included. The geographical distribution of the average organic-carbon content in soils of the Russian tundra zone exhibits definite latitudinal and longitudinal patterns. On the Kola Peninsula, the highest average values were obtained for tundra bogs, river floodplains, and forest-tundra bogs; in the Eastern European province and the Polar Urals, for forest-tundra and forest-tundra bogs; in Siberia, for Arctic-tundra and typical-tundra bogs; and in Chukotka, for the forest-tundra with abundant siberian dwarf-pine elfin woods. Other authors have also reported on the zonal pattern of the distribution of organic-matter and soil-carbon content, namely, an increase in this content in the direction from Arctic deserts to southern tundra, except for bog areas (Ignatenko, 1964; Ignatenko *et al.*, 1973; Bazilevich, 1993).

The zonal characteristics of the distribution of average resources considerably affect the total resources. As a result, the ranks of elementary areas according to total carbon content substantially differ from their ranks according to area (Table 1). For example, forest-tundras of the Eastern European province and Central Siberia have the highest total resources (1982×10^{12} and 1907×10^{12} kg, respectively), whereas the Central Siberian Arctic tundras and the Far Eastern typical tundras are the largest (23.05×10^6 and 20.42×10^6 ha).

The total estimated carbon content in the soils of all Russian tundra and forest-tundra ecosystems (279×10^6 ha) is 28.6×10^{12} kg (Table 2). The European part of Russia accounts for approximately 21% of the total resources of soil carbon; most of the resources (17%) are located in the Eastern European tundra, and only 4%, on the Kola Peninsula and in the Polar Urals.

The greatest carbon resources are located in larger areas, namely, in Central Siberia and the Chukotka–Anadyr' province (8.6×10^{12} and 4.7×10^{12} kg); the Kola Peninsula and Polar Ural resources are the smallest (0.7×10^{12} and 0.4×10^{12} kg).

According to our estimation, the average carbon content in the Russian tundra is 103×10^3 kg/ha; it varies from 23×10^3 to 321×10^3 kg/ha in Arctic deserts and forest-tundra bogs, respectively. According to the data reviewed by Kobak (1988), these average values vary from 50 to 200×10^3 kg/ha in the tundra and from 27 to 232×10^3 kg/ha in Arctic yerniks (dwarf–birch thickets). In Alaska, the average content of soil carbon varies from 142 to 324×10^3 kg/ha, depending on the soil type (Alexander *et al.*, 1989, cited in Eswaran *et al.*, 1993). Thus, our estimations are within the range of those reported by other authors.

Before we turn to a comparison of independent total regional and zonal values, note that the differences between them are explained by (1) differences in the average values that were used as originals and (2) differences in area estimations. As noted above, we estimated the areas based on a landscape map, whereas other researchers use soil maps (Rozhkov *et al.*, 1997), reference data on ecological and agricultural regions (Biryukova and Orlov, 1993; Orlov *et al.*, 1996), or other types of landscape maps (Kolchugina and Vinson, 1993). Soil types are often assumed as the basis for

Table 1. Average and total carbon resources in the soil organic matter in Russian tundra landscapes

Zonal and mountain landscapes				Intrazonal landscapes within zonal and mountain landscapes					
				bogs			river floodplains		
type	area, 10^6 ha	organic-carbon content		area, 10^6 ha	organic-carbon content		area, 10^6 ha	organic-carbon content	
		average, 10^3 kg/ha	total, 10^9 kg		average, 10^3 kg/ha	total, 10^9 kg		average, 10^3 kg/ha	total, 10^9 kg
Kola Peninsula									
Mountain deserts	0.05	23.4 ± 2.5	1 ± 0		No data			No data	
Mountain tundra	0.45	53.3 ± 18.4	24 ± 8	0.26	204.0 ± 46.4	53 ± 12	0.10	128.7 ± 55.4	13 ± 6
Southern tundra	1.90	99.9 ± 29.1	190 ± 55		No data			No data	
Forest-tundra	3.12	108.1 ± 36.4	337 ± 113	0.32	321.1 ± 139.2	102 ± 44		No data	
Total	5.51	100.1 ± 32.1	552 ± 177	0.58	268.7 ± 97.7	155 ± 56	0.10	128.7 ± 55.4	13 ± 6
The Eastern European province									
Arctic tundra	1.67	68.5 ± 18.5	114 ± 31		No data			No data	
Typical tundra	4.55	79.2 ± 25.0	361 ± 114	0.45	155.1 ± 38.3	70 ± 17	0.12	179.1 ± 59.8	21 ± 7
Southern tundra	11.92	141.4 ± 60.0	1686 ± 715	1.12	321.1 ± 139.2	361 ± 156	0.64	179.1 ± 59.8	115 ± 38
Forest-tundra	6.38	310.8 ± 126.3	1982 ± 805	0.40	321.1 ± 139.2	128 ± 56	0.13	192.0 ± 60.7	25 ± 8
Total	24.53	168.9 ± 67.9	4143 ± 1666	1.97	283.2 ± 116.2	559 ± 229	0.89	181.0 ± 59.9	161 ± 53
The Polar Urals									
Mountain Arctic deserts	0.68	23.4 ± 2.5	16 ± 2		No data			No data	
Mountain tundra	1.82	105.5 ± 23.6	192 ± 43		No data		0.02	128.7 ± 55.4	3 ± 1
Typical tundra	0.02	79.2 ± 25.0	2 ± 1		No data		0.00	179.1 ± 59.8	1 ± 0
Southern tundra	1.02	141.4 ± 60.0	144 ± 61		No data		0.09	179.1 ± 59.8	16 ± 5
Forest-tundra	0.09	191.1 ± 69.7	17 ± 6		No data			No data	
Total	3.63	102.2 ± 31.0	371 ± 113		No data		0.11	170.3 ± 59.0	19 ± 7
Islands of the Barents and Kara seas									
Glaciers	6.06	0	0		No data			No data	
Arctic deserts	4.18	23.4 ± 2.5	98 ± 10		No data			No data	
Arctic tundra	2.30	57.6 ± 3.4	132 ± 8		No data			No data	
Total	12.54	18.4 ± 1.5	230 ± 18		No data			No data	
Western Siberia									
Arctic tundra	6.50	57.6 ± 3.4	374 ± 22	0.68	212.8 ± 50.4	145 ± 34	0.83	100.7 ± 30.4	84 ± 25
Typical tundra	10.95	79.5 ± 9.2	871 ± 101	0.55	155.1 ± 38.3	85 ± 21	1.60	179.1 ± 59.8	287 ± 96
Southern tundra	11.10	83.3 ± 20.3	924 ± 226	0.71	151.7 ± 47.1	108 ± 33	2.41	179.1 ± 59.8	432 ± 144
Forest-tundra	3.52	66.7 ± 11.5	235 ± 41	0.16	151.7 ± 47.1	24 ± 8		No data	
Total	32.07	75.0 ± 12.1	2404 ± 389	2.10	172.4 ± 45.9	362 ± 96	4.84	165.7 ± 54.8	802 ± 265

Table 1. (Contd.)

Zonal and mountain landscapes				Intrazonal landscapes within zonal and mountain landscapes					
				bogs			river floodplains		
type	area, 10^6 ha	organic-carbon content		area, 10^6 ha	organic-carbon content		area, 10^6 ha	organic-carbon content	
		average, 10^3 kg/ha	total, 10^9 kg		average, 10^3 kg/ha	total, 10^9 kg		average, 10^3 kg/ha	total, 10^9 kg
Central Siberia									
Arctic deserts	2.75	23.4 ± 2.5	64 ± 7		No data			No data	
Mountain Arctic deserts	2.77	23.4 ± 2.5	65 ± 7		No data			No data	
Mountain tundra	13.54	86.3 ± 9.4	1169 ± 127		No data		0.29	128.7 ± 55.4	37 ± 16
Arctic tundra	23.05	57.6 ± 3.4	1327 ± 78		No data		1.98	100.7 ± 30.4	199 ± 60
Typical tundra	17.03	85.9 ± 22.0	1463 ± 375	0.17	155.1 ± 38.3	26 ± 6	2.41	179.1 ± 59.8	431 ± 144
Southern tundra	10.80	121.2 ± 43.2	1309 ± 466	0.03	147.8 ± 54.0	4 ± 2	1.24	179.1 ± 59.8	222 ± 74
Forest-tundra	13.12	145.4 ± 65.5	1907 ± 859	0.11	147.8 ± 54.0	16 ± 6	1.86	192.0 ± 60.7	557 ± 113
Total	83.06	87.9 ± 23.1	7304 ± 1919	0.31	152.0 ± 45.4	46 ± 14	7.78	160.4 ± 52.4	1247 ± 407
The Yakut province									
Mountain tundra	9.10	79.4 ± 14.5	723 ± 132		No data		0.56	128.7 ± 55.4	72 ± 31
Arctic tundra	10.11	91.5 ± 8.6	925 ± 87	0.06	212.8 ± 50.4	12 ± 3	3.45	100.7 ± 30.4	347 ± 105
Typical tundra	12.39	104.4 ± 29.8	1293 ± 370		No data		2.93	179.1 ± 59.8	525 ± 175
Southern tundra	1.31	121.2 ± 43.2	159 ± 57		No data		0.10	179.1 ± 59.8	18 ± 6
Forest-tundra	7.56	145.4 ± 65.5	1099 ± 495		No data			No data	
Total	40.48	103.7 ± 28.2	4199 ± 1140	0.06	212.8 ± 50.4	12 ± 3	7.04	136.7 ± 45.1	962 ± 317
Islands of the Laptev, East Siberian, and Chukchi seas									
Glaciers	0.01	0.0	0		No data			No data	
Arctic deserts	0.81	23.4 ± 2.5	19 ± 2		No data			No data	
Mountain tundra	0.48	79.4 ± 14.5	38 ± 7		No data			No data	
Arctic tundra	3.20	87.7 ± 14.0	281 ± 45		No data			No data	
Total	4.50	75.1 ± 12.0	338 ± 54		No data			No data	
The Chukotka–Anadyr' province									
Mountain Arctic deserts	3.10	23.4 ± 2.5	73 ± 8		No data			No data	
Mountain tundra	11.87	85.0 ± 35.1	1009 ± 417		No data		0.22	128.7 ± 55.4	28 ± 12
Arctic tundra	1.11	91.5 ± 8.6	102 ± 10		No data		0.04	100.7 ± 30.4	4 ± 1
Typical tundra	0.77	104.4 ± 29.8	80 ± 23		No data		0.12	179.1 ± 59.8	22 ± 7
Far Eastern typical tundra	20.42	85.0 ± 35.1	1736 ± 717		No data		2.21	179.1 ± 59.8	396 ± 132
Forest-tundra	6.00	190.9 ± 68.1	1145 ± 409		No data		0.94	152.4 ± 68.1	143 ± 64
Total	43.27	95.8 ± 36.6	4145 ± 1582		No data		3.53	168.0 ± 61.4	593 ± 217

Table 2. Average and total carbon resources in the soil organic matter in the entire Russian tundra zone and its regions

Region	Area		Carbon content		
	10^6 ha	%	average, 10^3 kg/ha	total	
				10^9 kg	%
Kola Peninsula	6.19	2.2	116.2 ± 38.6	720 ± 239	2.5
The Eastern European province	27.39	9.8	177.5 ± 71.1	4863 ± 1948	17.0
The Polar Urals	3.74	1.3	104.2 ± 31.9	390 ± 119	1.4
Islands of the Barents and Kara seas	12.54	4.5	18.4 ± 1.5	230 ± 18	0.8
Western Siberia	39.01	14.0	91.5 ± 19.2	3568 ± 751	12.5
Central Siberia	91.15	32.7	94.3 ± 25.7	8598 ± 2341	30.0
The Yakut province	47.57	17.1	108.7 ± 30.7	5173 ± 1460	18.1
Islands of the Laptev, East Siberian, and Chukchi seas	4.50	1.6	75.1 ± 12.0	338 ± 54	1.2
The Chukotka–Anadyr' province	46.80	16.8	101.2 ± 38.4	4738 ± 1799	16.6
Total	278.89	100	102.6 ± 31.3	28619 ± 8729	100

Table 3. Estimated average and total carbon resources in the organic matter of soils of Russian and world tundras and forest-tundras

Region	Zone or soil type	Area, 10^6 km^2	Organic-carbon content		Source
			10^{12} kg	10^3 kg/ha	
European part of Russia	The Arctic-tundra zone, except for bogs and floodplains	0.37	3.0	80.8	This study
"	Zonal tundra soils	0.41	3.4	84.1	Biryukova and Orlov, 1993
Russia	The Arctic-tundra and forest-tundra zones	2.79	28.6	102.6	This study
"	The Arctic-tundra zone	2.35	21.1	89.7	This study
"	"	1.81	19.2	106.4	Orlov *et al.*, 1996
"	Tundra	2.14	43.7	204.0	Kolchugina, Vinson, 1993
"	Arctic, tundra, and mountain-tundra soils	2.16	40.2	185.9	Rozhkov *et al.*, 1997
"	Forest-tundra	0.44	7.5	172.0	This study
"	"	0.42	4.8	114.3	"*Uglerod v ekosistemakh...*", 1994
"	"	2.88	49.5	172.2	Kolchugina, Vinson, 1993
"	The forest-tundra–northern-taiga zone	2.34	39.4	168.5	Orlov *et al.*, 1996
The biome as a whole	Tundra and alpine ecosystems	8	163	204.0	Schlesinger, 1977
"	"	9.5	121	127.4	Ajtay *et al.*, 1979

territorial subdivision (Biryukova and Orlov, 1993; Orlov *et al.*, 1996; Rozhkov *et al.*, 1997). For correct comparison, we summarized the published data for the soil types corresponding to the tundra and forest-tundra zones.

The estimates of the area of the Arctic-tundra zone (without the forest-tundra) are similar in all studies (Table 3). They vary from 1.81 × 10^6 km^2 (Orlov *et al.*, 1996) to 2.35 × 10^6 km^2 (this study). In many of the studies reviewed (Orlov *et al.*, 1996; Kolchugina and Vinson, 1993), forest-tundras are combined with the northern taiga zone; therefore, the total estimated area of these two zones is substantially greater than our estimate of the forest-tundra area. An independent estimate of the area of forest-tundras per se (*Uglerod v ekosistemakh* ..., 1994) is close to our estimate.

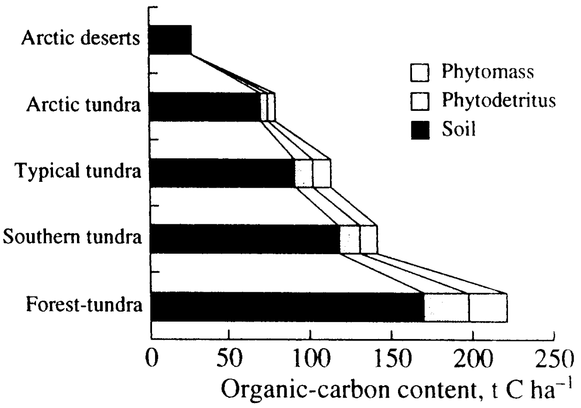
Estimates of the average carbon resources in the Arctic-tundra zone may be divided into two groups: (1) between 80 × 10^3 to 106 × 10^3 kg/ha (this study; Biryukova and Orlov, 1993; Orlov *et al.*, 1996) and (2) between 186 × 10^3 and 204 × 10^3 kg/ha, i.e., about twice as large (Rozhkov *et al.*, 1997; Kolchugina and

Vinson, 1993). The reasons for these considerable discrepancies are unclear; we may assume that these are related to underestimation of the latitudinal differences in the distribution of the average carbon content in soil. For example, Rozhkov *et al.* (1997) estimated the average carbon content in flatland Arctic soils to be as low as 50×10^3 kg/ha, with these soils occupying only 11% of the total tundra area. According to our estimation, the total area of Arctic deserts and Arctic tundras accounts for approximately 30% of the area of the tundra zone, and their average carbon content is 69×10^3 kg/ha. Kolchugina and Vinson (1993) use the same average estimate (200×10^3 kg/ha) for all zonal tundras. The estimates of the average carbon resources in forest-tundras and northern taiga reported by different authors (Table 3) are similar to one another (between 169 and 172×10^3 kg/ha), except for one underestimated value of 114×10^3 kg/ha (*Uglerod v ekosistemakh ...*, 1994).

These differences in the estimates of the average carbon resources lead to discrepancies in the estimates of the total amount of soil carbon in the Arctic-tundra zone of Russia. In the aforementioned two groups of studies, these estimates vary from 19.2×10^{12} to 21.1×10^{12} kg (Orlov *et al.*, 1996; this study) and from 40.2×10^{12} to 43.7×10^{12} kg (Rozhkov *et al.*, 1997; Kolchugina and Vinson, 1993). These considerable discrepancies indicate that the question discussed remains unsolved as regards the Arctic-tundra zone of Russia.

Note that the aforementioned studies were aimed at estimation of the total soil-carbon resources in Russia; therefore, the researchers did not pay much attention to the division of territories into tundras and forest-tundras. The goal of this study was narrower (we only dealt with tundras and forest-tundras); therefore, we analyzed both the intrazonal and regional distributions of the soil carbon content in more detail.

The generalized estimates of the average carbon resources in the world tundra biome also vary considerably. They range from 127×10^3 kg/ha (Ajtay *et al.*, 1979) to 204×10^3 kg/ha (Schlesinger, 1977). The former estimate is comparable with the estimate obtained in this study (103×10^3 kg/ha), especially if we take into account that the largest regions of the Russian tundra (in Western and Central Siberia) are located in the Far North. If we assume the total amount of carbon in soils of the world tundra biome to be 121×10^{12} kg (Ajtay *et al.*, 1979), then Russian tundras and forest-tundras account for 24% of this amount.



The average carbon content of soil, phytodetritus, and phytomass in zonal landscapes of the Russian tundra zone.

The total carbon content in the phytomass of Russian tundras and forest-tundras (excluding Far East dwarf-pine elfin woods) is 2.6×10^{12} kg (Karelin *et al.*, 1995). According to Bazilevich (1993), the ratio of the mass of plant remnants (phytodetritus) to the phytomass of live plants is 1.2–1.3 in zonal types of tundra and 1.8 in mountain and hydromorphic landscapes. Based on these data, the amount of organic carbon in tundra phytodetritus may be estimated at 3.5×10^{12} kg, and its total amount in Russian tundra and forest-tundra ecosystems, at 34.7×10^{12} kg, with the proportion of carbon in the soil organic matter being 82%. Note that the average carbon content both in the soil and in the phytomass and phytodetritus regularly decreases from forest-tundras to Arctic deserts (figure). However, this is accompanied by an increase in the proportion of soil carbon in the total amount of carbon in the ecosystem; these proportions are 75, 82, 81, 93, and 94% in forest-tundras, southern tundras, typical tundras, Arctic tundras, and Arctic deserts, respectively.

The results obtained in this study are a step towards the refinement of these values at both the regional and global levels. These data may be used as an empirical basis when constructing corresponding mathematical models, including those designed for predicting the effect of climatic changes on the biosphere.

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