Working Paper

Soil Carbon Estimates and Soil Carbon Map for Russia

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D.E. Konyushkov, S. Nilsson, V.B. Sheremet,
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WP-96-60
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Foreword

Siberia's forest sector is a topic which recently has gained considerable international interest.

IIASA, the Russian Academy of Sciences, and the Russian Federal Forest Service, in agreement with the Russian Ministry of the Environment and Natural Resources, signed agreements in 1992 and 1994 to carry out a large-scale study on the Siberian forest sector. The overall objective of the study is to focus on policy options that would encourage sustainable development of the sector. The goals are to assess Siberia's forest resources, forest industries, and infrastructure; to examine the forests' economic, social and biospheric functions; with these functions in mind, to identify possible pathways for their sustainable development; and to translate these pathways into policy options for Russian and international agencies.

The first phase of the study concentrated on the generation of extensive and consistent databases of the total forest sector of Siberia and Russia.

The study is now working on its second phase, which will encompass assessment studies of the greenhouse gas balances, forest resources and forest utilization, biodiversity and landscapes, non-wood products and functions, environmental status, transportation infrastructure, forest industry and markets, and socio-economics.

This report, carried out by a team from the Dokuchaev Soil Institute in Moscow under the leadership of Professor Rozhkov and Professors Shvidenko and Nilsson from the Study's core team, is a contribution to the analyses of the topic of greenhouse gas balances.

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1. Introduction

The problem of evaluation of the reserves and balance of carbon in various components of ecosystems and in the biosphere as a whole has a long history. Over decades this problem has attracted the attention of different specialists — geologists and geochemists, climatologists and meteorologists, biologists physiologists of plants, ecologists, and pedologists. Within the last decades the interest in these questions has become especially intense; the studies have switched from pure theoretical constructions to the stage of practical organization of a global network of monitoring the concentration of carbon-bound compounds in various components of the environment and to elaborate strategic and concrete measures aimed at maintenance of geochemical stability of natural cycles of carbon, and to mitigate currently observed increases in concentration of carbon in the atmosphere. This is primarily related to the growing concern of scientists about the possibility of global warming due to increased concentration of greenhouse gases in the atmosphere. Evidently, such warming would involve drastic changes in the biosphere and, hence, in the world economy.

2. General Problems

2.1. Geochemical History of Carbon on the Earth

Carbon, together with oxygen and nitrogen shares the third — fifth place (after hydrogen and helium) in abundance in the Universe (Voitkevich et al., 1990), and ranks among the second ten of the elements, composing our planet. Its content in the planet makes up approximately $n \cdot 10^{18}$ tons (Uspenskii, 1956; Kovda, 1985), that is just a split percent in comparison with the total mass of the Earth ($6 \cdot 10^{21}$ tons). However, the role of carbon on the planet can hardly be overestimated.

Geochemical history of carbon on the Earth is determined by the history of appearance and evolution of life on our planet. As it was vividly stated by Vernadskii (1994) "geochemistry of carbon cannot be understood beyond the phenomena of life."

During the pre-biogenic period of the evolution of the Earth, accumulation of simple carbon-containing molecules (CO_2, CO, CH_4) in the Earth's crust, atmosphere, and hydrosphere was conditioned by the process of differentiation of mantle and degasification of magma. Immense amounts of carbon were delivered to the surface in the course of volcanic eruptions, especially, during the periods of activation of ancient tectonomagmatic cycles. The total amount of carbon, accumulated in the upper geospheres of the planet is assessed at $n \cdot 10^{16\text{-}17}$ tons (Kovda, 1985; Ronov, 1993). Emanation of carbon from the deep layers of the planet takes place at present as well. Its intensity was assessed by Goldschmidt (1954) at 1.5-3.0·10^7 tons per year (for CO_2), that is approximately n·10^6 tons C annually. Already during the first stages of the evolution of the planet these processes resulted in the formation of the atmosphere and hydrosphere with high content of carbon dioxide.

Within recent years, due to the studies of the isotopic composition of carbon in various natural objects, Galimov (1988) suggested the new hypothesis about the origin of the initial carbon on the planet. His studies suggest that there are two forms of carbon different in their isotopic composition. Carbon contained in the rocks of the Earth's mantle is enriched in "light" isotope (^{12}C), whereas carbon contained in the rocks of the Earth's crust is enriched in "heavy" (^{13}C) isotope, and the ratio between isotopes is similar to the carbon contained in carboniferous stony meteorites (chondrites). The author explains this by the heterogeneity of the initial material that composed the planet, attributing its origin to different stages of cosmic nucleogenesis. He suggests that carbon of mantle rocks could originate from initial protoplanet substances (cloud) that had experienced a stage of high temperature accretion with the release of most of volatile components. The reason of the enrichment of the rocks of the Earth's crust with "heavy" isotopes of carbon, according to Galimov, could be the meteorite "bombing" of the planet after the end of the main stage of accretion. This "bombing" was synchronous with the stage of analogous "bombing" of the Moon, which has been confirmed by different scientists. As a result of this process, the Earth could gain most of its volatile components, including water vapor, and the initial hydrosphere was formed. Probably the carboniferous substances of chondrites could give rise to the origin of molecules performing the photosynthetic reactions of the destruction of water molecules with the release of free oxygen, which, in turn, were the main prerequisites of the origin of life on our planet. This interesting hypothesis requires further examination; however, it is important that it entails the problem of the origin and evolution of life on our planet and the problem of geochemical history of carbon with the more general problems of the evolution of the Universe.

With the appearance of life on the Earth (3.2-3.8 billion years ago) and the beginning of the development of the biosphere, the fate of carbon on the planet was conditioned by its involvement into biogenic cycling of substances. As early as in the Archean era, the accumulation of carbon in primary living organisms resulted in the decrease in the partial pressure of carbon dioxide in the ocean, which, in turn, led to intensive sedimentation of carbonates.

The development of photosynthetic organisms gradually involved the accumulation of free oxygen and the establishment of oxidizing conditions. In the Riphean period (1.7-0.7 billion years ago) the bulk of carbon dioxide of the atmosphere and hydrosphere was fixed in chemogenic and biochemogenic (stromatolitic) calcareous sediments. Probably this strong uptake of carbon from the atmosphere was one of the reasons of the first (Early Proterozoic and Riphean) glaciations of the planet.

According to the hypothesis of Vinogradov (1967), the continuing decrease in concentration of CO_2 in sea waters during the Vendian period (due to sequestration of carbon in the living matter) resulted in a relative stability of calcium carbonates in the upper layers of the ocean. This ensured active development of marine organisms with calciferous shells during the Cambrian period. During the following evolution of life during the whole Phanerozoic time, carbonate sedimentation in oceans was predominantly biogenic; over time, an increase in the proportion of calcite minerals in carbonate sediments was observed.

Due to the rapid development of terrestrial vegetation in the Devonian and, especially, in the Carboniferous periods, huge masses of carbon were accumulated in buried organic residues that served as the sources of coal and deposits.

During the Mesozoic era, characterized by the increased concentration of oxygen in the atmosphere and, hence, accelerated processes of oxidation, the intensity of formation of coal deposits was lowered. This stage is denoted by the appearance of new forms of life in the ocean and on the land surface.

Intensive inflow of CO_2 into the atmosphere was observed during the beginning of the Alpine tectogenesis. Due to intensification of volcanic eruptions, the concentration of CO_2 in the atmosphere amounted to 0.8%. As a consequence, the rapid development of photosynthetic plants, the propagation of the new forms of plants (Angiospermae), widespread of forest landscapes, accumulation of lignite and lime formations took place.

However, as volcanic activity weakened and CO_2 accumulated in living matter and the products of its vital activity, the concentration of carbon dioxide in the atmosphere steadily decreased. As a result, during the Quaternary period it experienced periodic fluctuations within the limits, close to its current level. As evidenced by the data derived from the studies of ice cores from "Vostok" station in the Antarctica (Barnola et al., 1994), during the last 160 thousand years the concentration of CO_2 in the entrapped bubbles of atmospheric air ranged between 190 and 270-290 ppm; a high degree of correlation is observed between the increased or decreased levels of CO_2 concentration and the periods of interglaciations or glaciations, respectively.

After the last glaciation, the concentration of CO_2 in the atmosphere began to rise. The maximal rates of this process has been observed during the past two centuries and, especially, during the last fifty years. This rapid growth of CO_2 concentration is associated with the effects of economic activity of mankind, primarily, with the use of the reserves of organic carbon accumulated during the past geological periods (burning of fossil fuels) and with drastic decrease in the area of forest biomes on the planet, because of the needs of extensive agriculture.

At the same time, according to some estimates (Adams et al., 1990), the total amount of carbon in the terrestrial ecosystems of the Earth during the last 18 thousand years has increased by 1300 billion tons. Taking into account that the concentration of carbon in the atmosphere has increased as well, the authors come to the conclusion that the only source of "additional" carbon is the ocean, the reserves of carbon in which (in the form of dissolved CO_2) exceed the amount of carbon in the atmosphere and in terrestrial ecosystems by many times. It should be noted, however, that this estimation does not take into account the possible flux of carbon to the surface from the deep layers of the lithosphere and the mantle of the Earth in the course of volcanic activity.

This short review of the geochemical history of carbon on the Earth testifies that the main factor of redistribution of carbon between different components of the geosphere was the living matter. The Biotic component of the carbon cycle is "responsible" not only for the appearance of oxygen in the atmosphere and the formation of the immense reserves of carbon in the lithosphere (in the form of buried organic substances and carbonates), but also for the geochemical conditions and formation of the other types of sedimentary rocks. Thus, the living matter sustains the complex system of regulation of geochemical conditions in the biosphere, providing their relative stability and the possible existence and evolution of life on the planet. The hypothesis about the regulative role of living matter is laid in the basis of modern ecology (Odum, 1986). At the same time, studying the role of carbon cycling in the biosphere, we should not forget about the role of geological processes of carbon exchange between the biosphere and the interior of the Earth (lithosphere and the Earth's mantle). Ronov (1976, 1982) considers this exchange as a necessary prerequisite of sustainable development of life on the planet. His calculations suggest that the total reserve of "labile" carbon accumulated in the atmosphere, hydrosphere, living and extinct organisms of the biosphere ($43.5 \cdot 10^{12}$ tons) constitutes just a 0.00054 fraction of the amount of carbon accumulated in the Phanerozoic sediment rocks. Calculation of the rate of carbon accumulation in sediments testifies that the labile carbon of the biosphere can be expanded by the processes of sedimentation of carbonates less than in one million years, provided that there is no additional inflow of carbon from the Earth's interior. After this the reserves of carbon available for the synthesis of organic matter would be exhausted, the oxygen of the atmosphere (without its renewal in the course of photosynthesis) would be expanded by the processes of oxidation, and the life on the planet would cease. This scenario is possible in case that the reserves of radionuclides in the Earth would be exhausted and the tectonic activity of the planet would terminate. This remark seems rather important, because most of the studies of carbon cycling in the biosphere performed by ecologists ignore the role of geological processes and do not account for the vast data on carbon geochemistry gained by natural sciences, including geology, geochemistry, climatology, and meteorology. Precise assessment of the reserves of carbon in different components of the environment is possible if the data from different sources are correlated with each other. The brilliant example of such correlation is presented in a monograph by Uspenskii (1956). Extensive data on carbon geochemistry in various geospheres of the planet can be found in different studies (Budyko et al., 1985; Galimov, 1988; Gorshkov, 1980; Grigor'eva, 1980; Kobak, 1988; Kovda, 1976, 1979, 1985; Lisitsyn, 1978; Post et al., 1990; Ronov, 1976, 1982, 1993; Uspenskii, 1956; Vernadskii, 1994; Vinogradov, 1967; Woodwell et al., 1978, 1995).

2.2. Carbon in the Soil Cover of the Planet

Soil cover of the planet (pedosphere) represents the largest reserve of carbon in terrestrial ecosystems. In subaqual ecosystems the role of soil cover is played by lower deposits (pelosphere). Due to their location at the interface of different geospheres (atmosphere, hydrosphere, and lithosphere), soils serve as the "junction point" in which the intersection and interaction of the great geological and the local biological cycles of substances takes place. Soils are not only the result of the development of living matter on the Earth and the interaction of biota with exposed rocks, but also the major factor of existence and sustainable development of the biosphere (Fokin, 1994). Intensive biological cycling of energy and matter in soils ensures the supply of autotrophic plants with necessary nutrients. The transformation of dying biomass accompanied by the efflux of the accumulated, in the course of photosynthesis, carbon dioxide into the atmosphere takes place in soils as well. Soils serve as an important link of the hydrological cycle; the transformation of the composition of atmospheric precipitation in soils is one of the major controls of the composition of surface and ground waters, and river flows, and, consequently, the discharge of substances into the ocean basin.

Therefore, the role of soil in the regulation of global cycles of substances (including carbon) can hardly be overestimated. However, soils still remain one of the least studied carbon sinks. This is testified by the great scatter of assessments of the reserves of carbon in soils and by the absence of commonly accepted methods of such assessments, in particular the methods of evaluation of stable and labile compounds of organic-bound carbon.

The essence of soils as bio-abiotic (biocosic) natural bodies is specified by the processes of interaction of living and inert organic matter with mineral matrix and with the formation of a very complex system of the products of such interactions. Thus, the structure and composition of carbon reserves in soils is very complex as well, which is not always properly considered by scientists. Evidently, soil is not only the most important sink of atmospheric carbon (due to the transformation and translocation of labile carbon compounds participating in the biological cycle into relatively stable reserves of humus substances, and, finally into the carbon compounds of lithified sediments participating in the geological cycle of substances with the mean residence time measured in millions and billions of years), but also (and simultaneously) as a source of carbon dioxide and reduced forms of carbon into the atmosphere, plants, and soil solutions, participating in hydrological cycle. Many aspects of the transformation of organic carbon compounds (decomposition of biomass, humification, and mineralization) and mineral forms of carbon (weathering, leaching, formation of pedogenic carbonates) are not sufficiently studied. In particular, the process of transformation of "lithogenic" carbonates into "pedogenic" ones requires further investigations. The latest study on the isotopic composition of soil carbonates suggests that this process is very active in the upper layers of the soil (Ryskov et al., 1995), though its role in the global carbon cycling is not clear at present. However, it is evident that the problem of mineral forms of carbon in soils deserves more attention; probably, the key to the puzzle of "missing" (Post et al., 1992) carbon can be found if more attention is paid to the mineral forms of carbon in soils.

The diversity of models describing carbon cycling in the ecosystems and the interrelations between climatic changes and the changes in carbon balance is substantial. Sometimes, quite opposite opinions are suggested. Not only the main trend of climatic change is important, but also the rate. For example, the model of interrelations between the content of organic carbon in soils and climatic changes proposed by Kirchbaum (1995) suggests that the "fate" of carbon in soils depends on the rate of temperature increase. The author concludes that at present the soils of cold regions of the planet serve rather as a source than a sink of atmospheric carbon (though northern ecosystems as a whole can function as absorbers of carbon); on the contrary, soils of tropical regions can accumulate some (minor) amounts of carbon. Experimental data of Zimov et al. (1993) on carbon emissions from permafrost-affected soils support the assumption that northern soils are a source of additional carbon.

However, there are other models, according to which the warming of the climate can result in additional sequestration of carbon in the tundra and in boreal forest ecosystems (Rastetter et al., 1991, 1992). Mathematical simulations of the cycles of carbon and nitrogen in soils, which take into account close linkages between the cycles of these elements, identify reserves of non-organic forms of nitrogen in soils, and the possibility of additional eutrophication of soils by nitrogen compounds due to technogenic pollution. These considerations are very important for elaboration of a general scheme for carbon cycling with due account for all possible internal and external factors.

It has been shown that even the "equilibrium" ecosystems can serve as a sink for atmospheric carbon due to its accumulation in the stores with great residence time (Lugo and Brown, 1986). Peat deposits, carbonate-bound compounds in soils, and hydrochemical discharge of carbon into the accumulative basins are considered to be such stores (Downing and Cataldo, 1992). Also, attention is paid to lacustrine ecosystems (Lugo and Wisniewski, 1992).

Obviously, the "key" point for studying the "long-term" reservoirs of carbon is the soil cover of the planet due to its indispensable role in the regulation of the processes of carbon exchange between atmosphere, lithosphere, and hydrosphere. The stock of carbon in soils (1500 billion tons, including 455 billion tons accumulated in peat) exceeds the amount of carbon in vegetation (500-600 billion tons) by three times and is twice as big as the amount of carbon in the atmosphere (750 billion tons) (Bolin et al., 1986; Houghton and Woodwell, 1989; Post et al., 1982, 1990; Gorham, 1990, 1991; Schlesinger, 1984; Tans et al., 1990; Woodwell et al., 1995). However, the variation in the available data on the reserves of carbon in soils is substantial. This is a result of lack of primary data, and differences in methodological approaches to soil sampling and soil analysis, methods of calculation, methods of estimating the bulk density of soils, and by the difficulties in the assessment of such parameters as the content of coarse fragments in soils, the content of plant roots in soils, and the share of non-soil and semisoil formations (rock outcrops, primitive soils) in the soil cover (Chapin and Matthews, 1993).

Probably one of the first attempts to calculate the reserves of organic carbon in soils of the planet was performed by Kononova (1976), who considered the mean content of humus substances in the main types of soils, and by Bazilevich (1974). Kobak (1988) estimated the reserves of carbon in soils to 2000 billion tons and revealed the dependence of the concentration of carbon in soils on the aridity index. On the basis of the work by Kobak, Kolchugina and Vinson (1993a) calculated the reserves of humus in soils of the former Soviet Union (404 ± 38 billion tons, including 148 billion tons accumulated in peat and bogs); the reserves of carbon in the litter layer was assessed to 18.9 ± 4.4 billion tons. These studies are interesting because of the attempt to distinguish the different groups of soil carbon, characterized by different mean residence time (turnover rate, or relaxation period). The group of carbon with the shortest turnover rate (t=2 years) was identified as the carbon of detritus in the litter layer; the groups of "labile" (t=480 years) and "stable" (t=1350 years) carbon were distinguished among humus substance (Kobak and Kondrasheva, 1993). In calculating the reserves of labile and stable carbon in soils it was assumed that labile carbon constitutes about 40% of the total amount of carbon in humus matter for all types of soils. Certainly, this assumption is open to argument and can be strongly criticized from the viewpoint of pedology. Also, it should be noted that the calculations of the authors were rather rough and did not account for the latest data of soil mapping and modern schemes of soil classification.

The first studies, in which the reserves of carbon (and nitrogen) in soils of the planet were estimated on the basis of the initial soil data treated by statistical methods, were the reports of the Oak Ridge National Laboratory (USA). The authors (Post et al., 1982; Zinke et al., 1984) collected and analyzed published data on more than 3,500 soil profiles throughout the world. Calculation of the reserves of carbon was performed with an allowance for bulk density of soils and the content of skeletal material in them. In cases, when the direct data on bulk density were absent, this parameter was estimated by the means of specially designed regression equations. Actual data on carbon concentration in various horizons of soils were re-calculated to standard depths. Finally, the estimations of the reserves of organic carbon for different natural zones, as well as for the whole area of terrestrial ecosystems were obtained. It was shown that the lowest concentrations of organic carbon constituted about 2 kg/m^2 (soils of arid regions) whereas the highest amounted to 30 kg/m^2 (in soils of humid alpine and subalpine meadows). The global "soil pool" of organic carbon was assessed at 1309 billion tons (if calculated on the basis of the data on the average content of carbon in soils of a particular biome), or at 1728 billion tons (if calculated on the basis of the weighted average data on the reserves of soil carbon along the parallel (in latitudinal zone)). It should be noted that the calculation of areas was performed not on the soil map, but on the map of the main ecosystems of the Earth. Also, the authors collected the data of other researchers. The degree of differences between the assessments (from 700 billion tons (Bolin, 1970) to 2070 billion tons (Ajtay et al., 1979)) testified that the problem of global assessments of carbon reserves in soils was far from being solved. The authors analyzed the methodological problems of such assessments. Actually, these problems have not yet been solved, although a lot of new assessments have been performed during the past decade (Kobak, 1988; Tans et al., 1990).

A great number of studies are devoted to regional or "ecosystem" assessments of carbon reserves in soils (Amacher et al., 1986; Apps and Kurz, 1992; Apps et al., 1993; Bazilevich et al., 1993; Billings et al., 1982; Botch, 1993; Cerri, 1994; Chapin and Matthews, 1993; Cherkinsky and Goryachkin, 1993; Cihlar and Apps, 1993; Houghton, 1991, 1993; Kolchugina and Vinson, 1993a, 1993b, 1994; Kurz and Apps, 1993, 1994; Matthews and Fung, 1987; Nabuurs and Mohren, 1993; Orlov and Biryukova, 1995; Shvidenko et al., 1994; Tarnocai, 1989, 1994; Tarnocai et al., 1993). In this chapter, a brief review of the experiences in this field is presented.

Specialists from the Forest Service of Canada have carried out a large-scale project on the assessment of the carbon budget in forest ecosystems of the country. The first stage of this project aimed at elaboration of the system of indices characterizing the content and the dynamics of carbon in forest ecosystems (i.e. the scheme of carbon turnover in forests) and at estimation of carbon reserves in the main "blocks" of the system. It was supposed that during the following stages the model of interrelations between carbon cycling and climatic changes would be created and the models of optimization of forest management would be tested (Kurz et al., 1992). The "soil" block of the model of carbon turnover includes three different pools of carbon: "labile" (period of half-decay of carbon compounds equals to 3-20 years, dependent on the ecoclimatic province) is represented by the upper 10 cm layer of the forest litter; "medium" (20-100 years; lower part of the litter layer), and "slow" (> 100 years; humus substances of soils). Data on the forest inventory performed by Canadian Forestry, and on the inventory of bogs were used for the database. The authors mention that the data are sometimes "overlapping" and the degree of this overlapping is not always certain, therefore, accurate calculations are not always possible. The main "reference" year was 1986. According to the assessments, in 1986, soils of the Canadian forest sector contained 76.4 billion tons of carbon; the reserves of carbon in peat constituted 135 billion tons. The maximal concentration of carbon was found in soils of the Subarctic zone (up to 346 tons/ha) and the average concentration was estimated to 189 tons/ha. Annual influx of carbon to soils (with plant fall) constituted 17.3 million tons. In disturbed ecosystems, the influx of carbon to soils increases; however, the authors noted that the amount of data on the dynamics of carbon in soils after disturbances was insufficient.

At present, the authors of this work have created various models of carbon dynamics in forest ecosystems. The primary attention is focused on the "response" of particular biomes to climatic change (Cihlar and Apps, 1993; Price et al., 1993, 1994): The models also account for such factors of forest ecosystem development as the regime of disturbances, including fires, age and succession dynamics of forest, the rate of biomass increment and decomposition, intensity of forest industry, etc. (Kimmins et al., 1990; Kurz and Apps, 1994; Li and Apps, 1996; Kurz et al., 1995). Both regional and "national" as well as global models have been created (e.g. Apps and Kurz, 1992; Kurz and Apps, 1993). The authors have specially considered the problem of "scale transfer" of models (the use of local-scaled models for elaboration of regional, national, and global models). They believe that the solution of this problem can be found in elaboration of special "metamodels," in which the data of particular ecophysiological studies is correlated with the data on ecosystems' dynamics, which, in turn, are correlated with regional and global models for the carbon budget (Price and Apps, 1993).

It should be noted that within the framework of this Canadian study the estimation of the soil pool of carbon was performed without soil mapping data, collected by the Soil Survey of Canada. Soil scientists worked out their own project "Carbon Data of Canadian Soils" (Tarnocai et al., 1993; Tarnocai and Ballard, 1994). This project is based on the data of small-scale (1:1 M) mapping of Canadian soils for the whole territory of the country. Soil maps have been digitized; each of the polygons was characterized by an attribute table, describing the main natural (environmental) and soil features within a polygon, supplied by specially collected data for soil carbon. The database includes about 105,000 primary analytical data for estimation of carbon in soils. The calculations were performed for standard soil layers (0 - 30 cm, 0 - 100 cm), including litter layer and peat soils. The total amount of organic carbon in the upper layer is estimated to 70.1 billion tons; the amount of carbon accumulated in the upper meter of the Canadian soils constitutes 249 billion tons. Also, the calculations of the reserves of carbon in the main soil types of Canada and in the ecoclimatic provinces of the country have been performed. The procedures were thoroughly algorithmized; special classificators were developed for the database. The treatment of the data was performed with the use of the ARC/INFO program. The large amount of the initial data, thorough assessment of various soil properties (including the content of skeletal material and coarse organic fragments) make it possible to consider this work as the most currently profound and well substantiated attempt to evaluate carbon reserves in soils on a national level. However, this work does not account for different fractions of carbon in soils and does not provide the data required for understanding the relationships between "soil" and "biota" carbon pools. This circumstance substantially limits the possibilities to use the results obtained for calculation of carbon budget and forecasting the changes in carbon reserves of the ecosystems under global climatic changes.

Among the attempts to evaluate the reserves of carbon in the ecosystems, the efforts of West European scientists should be mentioned (Nabuurs and Mohren, 1993).

In general, rapid development of computerized technologies, which make the problem of treatment of large amounts of data much more easier, supports optimism that in the near future the number of studies devoted to calculations of carbon budget on the basis of the immense initial data obtained by different public and private institutions will be multiplied. To evaluate the reliability and feasibility of such calculations, special attention should be paid to the structure of parameters used in databases and the possibility to correlate the results of the studies for different components of the ecosystems.

3. Carbon in the Soils of Russia

3.1. Distribution of the Reserves of Organic Matter in the Soil Cover of Russia

According to Fridland (1972), soil cover is considered as a three-dimensional body, the area of which is predetermined by the total area of soils within a territory, and the vertical dimension by the thickness of the soils.

Geographical distribution of soils follows certain regularities, such as the horizontal (latitudinal) soil zonation, facial soil zonation, vertical soil zonation, and the irregularities of the formation of soil cover patterns (Dobrovol'skii and Urusevskaya, 1984).

It is beyond any doubt that the manifestation of humus formation processes in soil cover of Russia follows these regularities as well. Kononova (1968) noted that the character of organic matter in soils to a large extent controls the direction of soil formation, and Ponomareva (1956) considered that the term "types of soil formation" is almost a synonym of the term "types of humus formation."

Two trends can be distinguished in modern Russian approaches to study soil humus: zonal-genetic and profile-genetic (Dergacheva, 1984; Orlov, 1974; Ponomareva and Plotnikova, 1980).

The problem of geographical regularities of humus formation was originally set up by Dokuchaev (1883) in his classical study "Russian Chernozem." The map of the Chernozemic zone of the European part of Russia, included in his book, represented the areas with equal content of humus in the topsoil (isohumus strips). The distribution of these strips revealed the geographical regularity in the content of humus. The isohumus strip with a maximal content of humus (13-16%) occupied the central and the Trans-Volga areas of the Chernozemic zone; to the north and to the south of this line the content of humus in soils decreased.

In order to characterize humus formation quantitatively and to calculate the reserves of humus in soils, it is necessary to obtain the data on humus content in each horizon of the soil profile.

On the basis of the average data on humus content in different soils of the USSR, calculated by Bolotina (1947), Tyurin (1949) compiled general tables on the reserves of humus in the upper 20 cm and in the upper meter of the main soil types of the Soviet Union (Table 1).

The analysis of these data enabled Tyurin to formulate the following regularities of the zonal distribution of humus substances in the soils of the USSR:

(a) In soils of the automorphic (eluvial) position, the maximum degree of accumulation of humus is observed in Deep Chernozems.

(b) In soils, located to the north and to the south of the subzone of Deep Chernozems, the reserves of humus gradually decrease; the rate of this decrease is higher in the southern direction.

(c) The differences in the reserves of humus among different soils are more vividly expressed for the layer 0-100 cm, as compared to the layer 0-20 cm.

(d) The proportion between the reserves of humus in the layers 0-20 cm and 0-100 cm varies in dependence on the character of profile distribution of humus content in soils. In soils of forest landscapes, characterized by a rapid decrease in the content of humus with depth, the upper 20 cm layer contains almost 50% of the total amount of carbon in the 0-100 cm layer. In soils of steppe landscapes, the share of the upper 20 cm layer in the total reserve of humus decreases to 24-32%; soils of drier regions (i.e. in Chestnut soils and Sierozems) occupy an intermediate position — the reserves of humus in the upper 20 cm constitute about 43-45% of the total reserves of humus in the upper meter of these soils.

Recently Orlov and Biryukova (1995) calculated the reserves of organic carbon in the top meter layer of the main soil types and of peat and bogs of Russia. Data for mountains and plain regions, as well as data for soils of agricultural use were separately distinguished (Table 2).

The average pool of organic carbon in the soils of Russia is estimated at 296 Gt, including 236 Gt in soils of plain territories and 60 Gt in soils of mountainous regions. The stores of organic carbon in arable lands constitute about 27 Gt, in other lands of agricultural use (meadows, gardens, fallow, etc.) 20 Gt.

Table 1. The reserves of humus in soils of the USSR, t/ha (Tyurin, 1949).

Soil Groups	**0 - 100 cm**	**0 - 20 cm**
Strong Podzolic	101	63
Podzolic	94	50
Weak Podzolic	104	54
Podzolic, average data:	**99**	**53**
Gray Forest, weakly podzolized soils of the forest-steppe zone	175	-
Dark Gray Forest soils	296	-
Forest-steppe podzolized soils, average data:	**215**	**109**
Chernozems:		
Degraded	452	132
Leached	549	192
Degraded and leached, average data:	**512**	**164**
Deep	709	224
Ordinary	426	137
Southern, West Ciscaucasian	391	93
Dark Chestnut soils	229	99
Chestnut and Light Chestnut soils	156	-
Sierozems:		
Dark Sierozems	128	-
Typical Sierozems	83	-
Light Sierozems	67	-
Sierozems, average data:	83	37
Red Earth soils (Krasnozems)	282	153

Table 2. The reserves of organic carbon in the top meter of soils and peat deposits of natural zones of Russia, 10^6 t (Orlov and Biryukova, 1995).

Soils	**Total Area, mln. ha**	**The Reserves of Organic Carbon**		
		Total	**Including:**	
			arable lands	other types of agricultural lands
Polar and Tundra zone				
Arctic and Arctic Tundra soils	51.7	4348.3	-	-
Tundra Gley soils	100.1	8941.6	-	-
Tundra Peat Bog soils	11.6	3027.8	-	-
Tundra Bog and Mucky-Peat soil	8.3	2907.9	-	-
Total:	180.7	19225.6	-	-
Forest-Tundra — Northern Taiga zone				
Gley-Podzolic, Podzols, Humus-illuvial, Gley Taiga Frozen, and Volcanic soils	159.2	5917.9	7.3	32.9
Podzolic-Bog and Alluvial soils	49.4	12699.1	28.7	114.6
Bog soils	25.0	20740.8	-	-
of which:				
Peat-bog soils	24.4	19828.5	-	-
Peat deposits of industrial value	0.6	912.3	-	-
Total:	233.6	39357.8	36.0	254.7
Middle Taiga zone				
Podzolic and Taiga Frozen soils	176.6	14312.7	81.1	196.9
Alluvial soils	12.6	2382.6	-	397.1
Podzolic-Bog soils	25.0	14124.1	-	226.0
Bog soils	23.6	21169.0	-	-
of which:				
Peat-Bog soils	20.3	16484.9	-	-
Peat deposits of industrial value	3.3	4684.1	-	-
Total:	237.8	51988.4	81.1	820.0
Southern Taiga zone				
Soddy Podzolic, Brown Forest, Brown-Taiga, and Sod-Calcareous soils	181.0	12741.2	1458.9	433.7
Alluvial soils	10.0	1653.1	82.7	446.3
Podzolic-Bog soils	18.1	10225.9	1977.4	3276.8
Bog soils	27.5	37332.0	98.0	2112.9
of which:				
Peat-Bog soils	6.7	5444.7	98.8	2112.9
Peat deposits of industrial value	20.8	31887.3	-	-
Total:	236.6	61952.2	3617.8	6269

Forest-Steppe zone				
Gray Forest soils	41.1	5626.2	1875.4	588.4
Chernozems	44.9	11563.6	8498.8	1442.2
Meadow-Chernozemic soils	13.5	4573.1	508.1	1355.0
Alluvial soils	6.0	2652.0	309.4	1414.4
Solods, Solonetzic complexes, Solonetzes	10.6	1949.9	142.5	549.7
Semi-Bog and Bog soils	6.0	12013.3	-	-
of which:				
Bog soils	3.6	9073.1	-	-
Peat deposits of industrial value	2.4	2940.2	-	-
Total:	126.4	38378.1	11334.2	5349.9
Steppe zone				
Ordinary and Southern Chernozems	43.8	11254.9	7854.3	2190.1
Chernozems with mycelium-calcareous horizons.	8.0	1958.2		
Meadow-Chernozemic and Chernozem-like	11.5	3637.2	1016.2	1592.1
Alluvial and Bog soils	4.0	2346.9	-	-
Solonetzic complexes, Solonetzes, Solonchaks	10.8	2150.7	692.2	1020.1
Total:	79.9	21347.9	9562.7	4802.3
Dry Steppe zone				
Dark Chestnut soils	6.6	976.2	976.2	-
Chestnut soils	7.7	625.3	235.5	365.4
Alluvial and Meadow-Chestnut soils	0.8	285.1	41.5	130.5
Solonetzic complexes, Solonetzes, Solonchaks	12.6	938.3	125.2	172.9
Total:	28.2	2824.9	1378.4	668.7
Semidesert zone				
Light Chestnut and Brown semidesert soils	2.2	121.8	72.5	49.4
Alluvial, Meadow-Chestnut, and Meadow-Brown soils	1.0	238.7	63.6	173.2
Solonetzes, Solonchaks, Solonetzic complexes	11.5	731.8	25.3	292.4
Total:	15.0	1092.3	161.4	515.0
Total for plain territories:	**1138.2**	**236167.2**	**26171.6**	**18022.2**
Caucasian Mountainous Region				
Mountainous Chestnut soils and Chernozems	3.1	611.6	97.9	416.1
Mountainous Brown Forest and Cinnamonic soils	2.9	312.9	-	-
Mountainous Meadow soils	1.0	102.1	-	-
Total:	8.2	1026.6	97.9	416.1
Southern Siberian Mountainous Region				
Mountainous Chestnut soils and Chernozems	5.0	1150.4	1024.7	125.7
Mountainous Gray Forest and Cinnamonic soils	15.0	2079.1	-	1572.6

Mountainous Brown Forest soils	8.0	863.1	-	-
Mountainous Podzolic and Taiga Frozen soils	206.7	13616.9	-	-
Bog (Peat Bog soils)	11.3	11149.2	-	-
Mountainous Meadow soils	2.0	204.2	-	-
Total:	248.0	29061.6	1024.7	1698.3
Northern Siberian Mountainous Region				
Mountainous Podzolic, Taiga Frozen, and Taiga Frozen Calcareous soils	132.8	8088.2	-	-
Peat Bog soils	2.9	2861.3	-	-
Peat deposits of industrial value	3.4	3875.5	-	-
Mountainous Meadow soils	4.2	233.9	-	-
Mountainous Tundra soils	150.0	12616.0	-	-
Total:	293.3	27674.9	-	-
Kamchatka-Kurilian Mountain Region				
Volcanic and Mountainous Sod-Calcareous soils	9.9	656.8	-	-
Mountainous Peat Bog and Alluvial soils	0.2	197.3	-	-
Mountainous Tundra soils	16.2	1362.5	-	-
Total:	26.3	2216.6	-	-
Total for Mountainous Regions:	**575.8**	**59979.7**	**1122.6**	**2112.4**
Total Russia	**1714.0**	**296146.5**	**27294.2**	**20136.7**

The zonal distribution of humus reserves is very distinct within the European part of Russia (as it was noted by Tyurin), whereas for the Siberian territory the general picture is much more complicated. This is explained by the fact that a considerable portion of Siberia is occupied by mountainous landscapes; thus the character of humus formation and accumulation in soils is controlled by the specifics of vertical zonation of soils. Also, vast areas within the West Siberian lowland are occupied by bogs, which stand out of the adjacent soils as having high humus reserves. However, the zonal regularity of humus distribution is observed in Siberian plains for the automorphic soils. The zones of tundra soils, the soils with low humus reserves (podzolic, taiga frozen soils), and the soils with high humus reserves (steppe soils) are vividly manifested.

Among the soils of the mountain regions of Russia, the main reserves of humus are concentrated within "zonal" types of soils. Humus reserves in the mountain territories of Siberia, a large portion of which is occupied by bogs, are characterized by a considerable contribution of organic soils to the total reserve of humus. The authors specially noted that the maximal reserves of humus are observed within the areas occupied by bog, peat-bog soils, and peats. The greatest share of these formations in the soil cover is observed within forest-tundra, northern taiga, and middle taiga zones.

Several estimates on the carbon reserves in the peat and bog ecosystems of Russia have recently been published. Alekseev and Berdsi (1994) estimate that the peat deposits contain 118 billion tons of organic carbon. Botch et al. (1995) estimate the total peatland area (precise definition of peatland is not presented) of the former Soviet Union to be 165 million ha and the corresponding carbon pool was estimated to 215 billion tons. Russia has about 98% of the peat- and boglands of the former Soviet Union. Thus, the Botch et al. (1995) estimate on organic carbon stored in peat- and boglands in Russia corresponds to some 210 billion tons. Probably, the most thorough and detailed analyses on the carbon storage in peat- and boglands in Russia have been carried out by Vompersky (1994) and Vompersky et al. (1994). The total area of peatlands and peat soils was estimated to 369 million ha (corresponding to 21.6% of the Russian territory). The areas with a peat layer thicker than 0.3 m was estimated to 139 million ha. The dominating part of the peatland areas are located in permafrost territories. These areas are dominated by bogged soils with a peat layer depth less than 0.3 m. The estimate on the total carbon storage in peatlands in Russia is 113.5 billion tons (97-133). The processes of bog formation and peat accumulation are inherent in the Boreal belt. Extensive bog ecosystems of Russia can be considered as one of the major potential sinks of carbon on our planet.

At present, a bulk of data on the humus reserves in different soils of Russia is accumulated. Most of the data are in agreement with the "traditional" concepts of general geographical regularities of carbon reserves in soils. However, many new particular regularities have been revealed recently.

Thus, the studies of the humus state of Chernozemic soils of Russia by Lebedeva (1992) enabled the author to refine the traditional notions on spatial changes in the processes of humus accumulation in Chernozems (the decrease in the content of humus and the thickness of humus horizon to the north and to the south of the subzone of Typical Chernozems, as well as along the West-East direction in accordance with the subzonal and provincial changes in climatic conditions). The real pattern of the humus distribution is more complicated. It was found that in the forest-steppe zone, the distinctions between different subtypes of Chernozems are rather low, especially in the topsoil layer; a regular decrease in the humus content along the gradient "Typical-Ordinary" Chernozems is observed only in the Trans-Volga region; provincial differences in the content of humus are not distinct for the Chernozems of the steppe zone, since the parameters of soil climate are rather even; subtype differentiation in the thickness of humus horizon among the Chernozems of the forest-steppe zone are conditioned not by climatic differences, but by the history of development of these soils, especially by the duration of the paleohydromorphic stage.

In addition to the studies of the zonal and provincial division of the soil cover of the country, a lot of research has been devoted to the studies of the soil cover structure within small territories. The basics of such studies were elaborated by Fridland (1972).

Detailed surveys of small experimental sites are aiming at an understanding of the regularities of the spatial variability of some soil features at the levels of "Elementary Soil Areas" (ESA) and "Elementary Soil Structures" (ESS) (i.e. inside ESA, at the level of individual soil bodies).

The studies of Soddy Podzolic soils on the territory of Zelenogradskaya experimental station of the Dokuchaev Soil Science Institute conducted by Prokhorova and Frid (1993) revealed that the coefficient of the spatial variability of the humus content (average level 1.58-1.80) within ESS makes up 20-23%, whereas within ESA it is equal to 15-16%. However, the amount of data on the variability of humus content within ESA and ESS (i.e. within natural soil bodies) is yet insufficient, though the data on local variability of this parameter is rather extensive. But, in the latter case, the objects of investigation are usually represented not by natural soil bodies, but by selected artificial fields, experimental plots, etc. Thus, the variability cannot be considered as a natural variation in humus content within an area of a particular soil.

A considerable contribution to the development of the zonal genetic studies of humus formation processes was made by Ponomareva. She can also be considered as one of the founders of the profile-genetic approach regarding the problems of humus formation. A thorough analysis of vertical distribution of humus in soils, qualitative composition of humus substances in different soils, and the interrelations between the processes of humus formation and other soil processes is presented in her studies (Ponomareva, 1964, 1974; Ponomareva and Plotnikova, 1980). She defined humus profile of steppe soils, Chernozems in particular, as a set of parameters characterizing the concentration of humus matter and its distribution along the whole profile of these soils.

Aleksandrova (1980) argued that the concept of humus profile should also include the data on the groups and fractions of humus substances, as revealing the proportions between different groups of humus and their interactions with the mineral matter.

According to Dergacheva (1984), the studies of the content and composition of humus within the whole soil profile should be aiming at revealing the specifics of organic matter in each soil horizon and in combination of such horizons. She defined a humus profile as "a set of chemically and genetically interrelated homogeneous zones (layers) of soil; each of such zones is characterized by specific combination of elementary processes of humus formation with a particular degree of their manifestation."

Organic matter of soils is often used as a diagnostic criteria of soil types. The system of parameters, characterizing the humus state of soils has been suggested by Grishina and Orlov (1978). This system allows to unify the diagnostic criteria and to evaluate such important soil characteristics as the content, reserve, and profile distribution of organic matter, nitrogen state of soil, the degree of humification, types of humus acids, fractions of humus acids, etc. According to Cherkinskii and Chichagova (1992) this system is suitable for mineral soils; however, it requires further improvement as concerns the soils with surface accumulation of organic matter, since such important parameters as the thickness and the content of humus in the litter layer are not included. Therefore, the authors argue that the more suitable concept for revealing the specificity of organic matter in soils is the concept of "organic profile." The latter concept was initially proposed by Grishina (1986), who defined the organic profile of soil as the organic component of the soil profile. Cherkinskii and Chichagova developed this concept and presented the definition of the "type of organic profile." According to this definition, the type of organic profile is a particular combination of quasihomogeneous interrelated organogenic and (or) organomineral zones, each of which has been formed by a corresponding set of processes of soil metamorphism with different degrees of evolution. They distinguished seven main types of organic profiles and attributed them to the corresponding types of world soils. Thus, the accumulative detrital, accumulative detrital-humus, accumulative isohumus, eluvial-illuvial humus, eluvial-humus, mineralizable humus, and humus-less types were identified and the small-scale schematic map of their distribution throughout the world was compiled. Later, this approach was used by Cherkinsky and Goryachkin (1993) for the assessment of carbon reserves in the soils of the European part of Russia .

3.2. Organic Matter of Soils and its Structural Components

Organic matter of soils is represented by an extremely complex and dynamic system of different substances. The dynamics of this system is conditioned by the regular addition of the residues of plant and animal matter to soils and their transformation under the influence of various groups of microorganisms and soil mesofauna. Some processes of transformation (oxidation, hydrolysis, mechanical decomposition) can occur under the direct impact of atmospheric precipitation, acid or alkaline conditions in soils, wind, and temperature fluctuations (Kononova, 1963). Aleksandrova (1980) considered the term "humus" as related only to soils; in her opinion, this term could be used to designate those organic substances in soils that had undergone the stage of humification. Other forms and products of transformation and accumulation of organic substances in the biosphere can be very similar to humus, but differ by their origin and, thus, should be considered as separate (individual) natural (or artificial) formations. The most detailed scheme for the main stages of the accumulation of organic substances in soil and their transformation was proposed by Aleksandrova (Figure 1).

Modern nomenclature for organic parts of soils was substantiated in the classical works of Tyurin (1937), Kononova (1963), and Aleksandrova (1980). Orlov (1985) used these nomenclatures in his general classification scheme for organic matter in soils (Figure 2). This nomenclature specifies organic matter of soils in terms of chemical compounds.

According to Orlov, "organic matter of soils" is the most general term that covers all organic substances of a soil profile, except for the living organisms. Humus is defined as the integrity of all organic compounds in soils except for the living organisms and their residues, which have not yet lost their anatomical structure. Specific humus substances are defined as the products of soil formation, more or less dark colored and composed of nitrogen-containing high-molecular organic compounds of acidic nature. Non-specific substances include the compounds, added to soil from decomposing plant and animal residues, with root excudations, etc. These substances (lignin, cellulose, proteins, amino acids, monosaccharides, waxes, fatty acids, etc.) are well-known in biochemistry.

According to Grishina (1986) litter formation is defined as the process of formation of the organogenic horizon of the mineral soil surface. This horizon is composed of 1-3 layers, representing successional stages of transformation of organic residues — from fresh foliage to humus formation. Forest litter is included in the soil profile. Usually, the following subhorizons are recognized: AO_l - foliage layer, which varies in the thickness over a yearly cycle; AO_f - fermentative layer, in which the most active transformation of organic residues takes place; AO_h - humus layer, composed of strongly decomposed organic residues and the products of their humification.

In order to classify the organic matter of forest soils (i.e. the total integrity of organic substances in the litter layer and humus horizon), the concepts of Mull, Moder, and Moor humus are used (Rode and Smirnov, 1972).

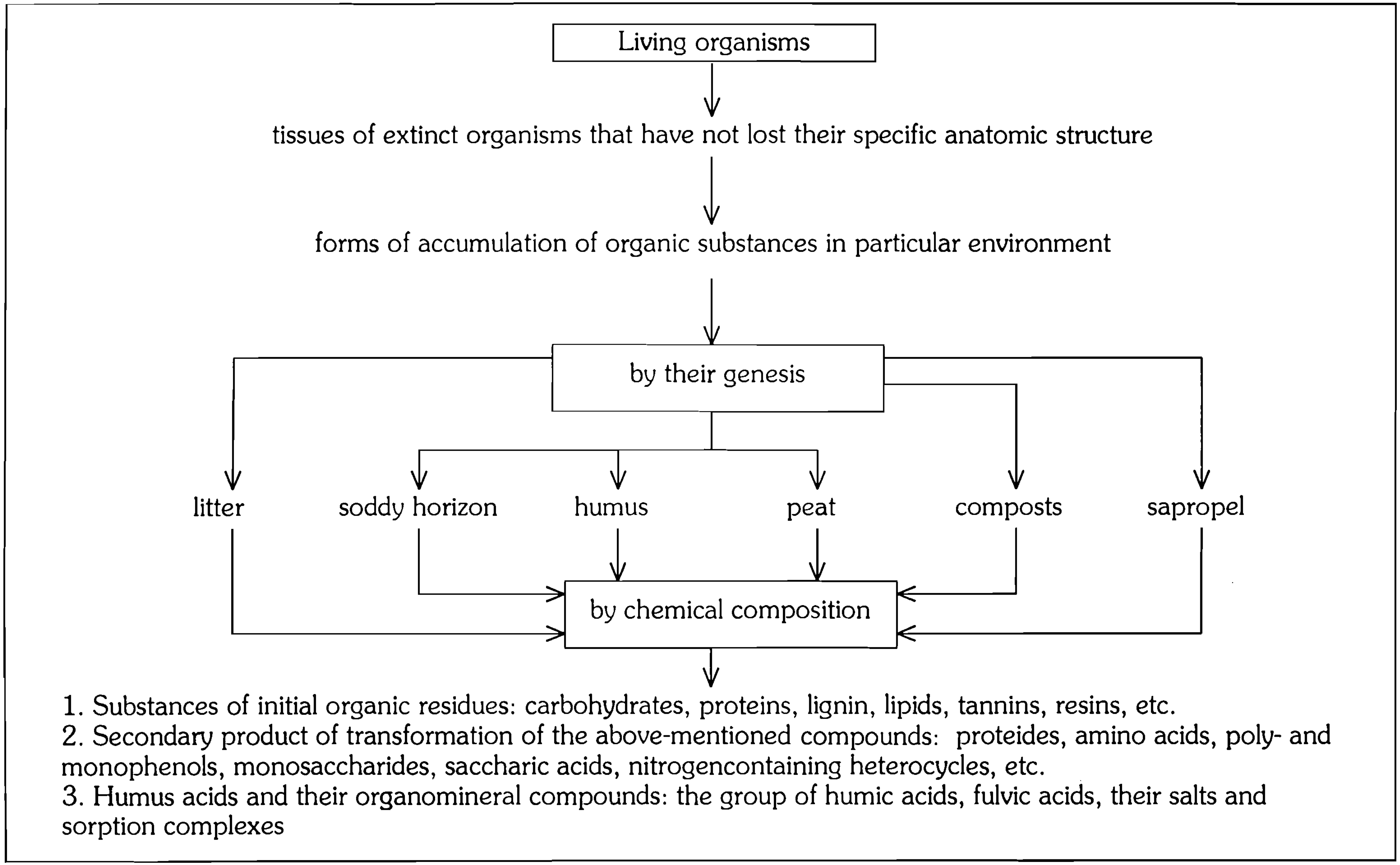
Mull type of organic matter is characterized by the presence of only one layer in the litter horizon (since the lower part of this horizon is mixed with the mineral layer and cannot be distinguished separately), and loose, well-structured (with grainy structure) humus horizon A1 of an increased thickness.

Moder type of organic matter is characterized by a two- or three-layered litter horizon with a distinct mucky layer at the point of contact of litter with mineral soil.

Moor (or mor) type of organic matter is identified by the presence of a thick 3-layered litter, slowly decomposing, rather compact, and easily separated from the underlying mineral soil.

Along with leaf foliage, soil surface in forests is covered by the coarse organic fragments (branches, trunks, boles, etc.), which should be separately distinguished (Bogatyrev, 1990).

Another specific component of topsoil was defined as detritus. According to Bogatyrev (1990), detritus is represented by finely dispersed humiferous plant residues, which have lost their anatomical structure. It can be derived from surface foliage, as well as from root residues (root debris).



1. Substances of initial organic residues: carbohydrates, proteins, lignin, lipids, tannins, resins, etc.
2. Secondary product of transformation of the above-mentioned compounds: proteides, amino acids, poly- and monophenols, monosaccharides, saccharic acids, nitrogencontaining heterocycles, etc.
3. Humus acids and their organomineral compounds: the group of humic acids, fulvic acids, their salts and sorption complexes

Figure 1. Products of the transformation of organic residues in the biosphere (Aleksandrova, 1980).

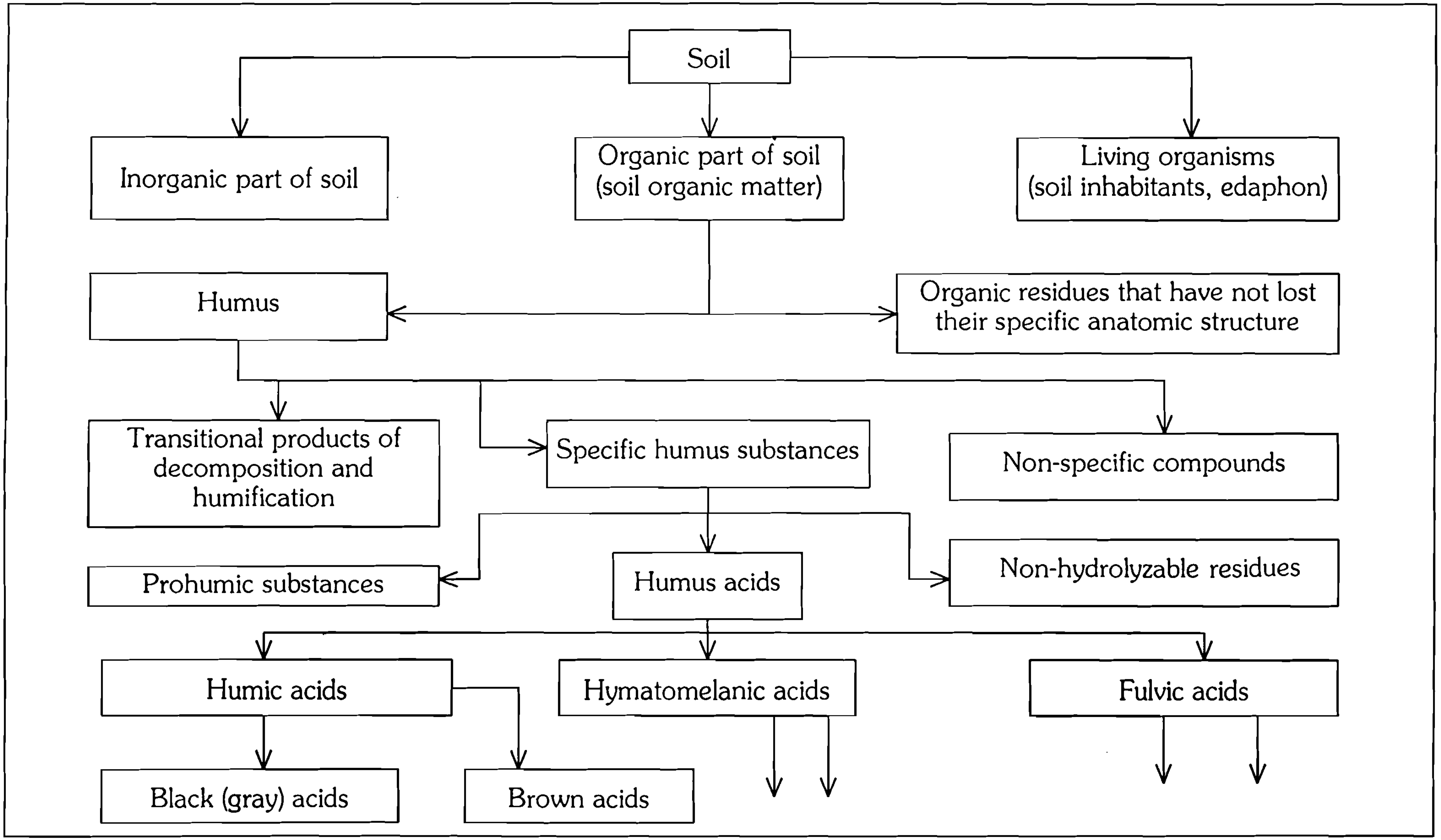


Figure 2. Nomenclature and division of humus substances in soils (Orlov, 1985).

Peat deposits and peat horizons are usually formed in poorly aerated conditions, and are almost permanently saturated with water. Only a limited number of species can exist in such conditions. Therefore, decomposition and humification of organic residues are very slow. Organic matter is accumulated in peat in the form of thick layers, saturated with water and composed of slightly transformed organic residues and the products of such transformation, in particular, lignin, which is released in the course of decomposition of cellulose. Peat has properties of semicolloidal systems. Inorganic parts of the peat are represented by various salts, primary and secondary minerals. The ash content of peat regularly increases with an increase in the degree of decomposition of peat. For practical purposes, peat is divided into groups of low, medium, and high ash content (<5%, 5-10%, and >10% of ash, respectively). Ash content in peat decreases with the change in the origin of peat — from low eutrophic moors to upland oligotrophic bogs (Lishtvan et al., 1989; Biryukova and Orlov, 1993). Lishtvan et al. (1989) have identified the following chemical compounds in peat: bitumen, water-soluble compounds, easily hydrolizable compounds, humic substances, cellulose, and non-hydrolizable residues (humins). The proportions between these compounds differ in various kinds of peat.

Differentiation of morphological and chemical composition of substances composing the organic matter of soils (and peat) is very important for the studies of the carbon cycling, since such data can provide the key to understanding the rate of biological turnover of carbon. Organic matter of soils can be divided into two categories according to its susceptibility to biological transformation. The first category (pool) is represented by labile organic substances, easily subjected to metabolic processes. The second is composed of relatively stable substances. Both pools play an important role in the functioning of ecosystems and contribute to their stability. The pool of labile substances is especially important for the cycling of biogenic elements (including carbon) within an ecosystem and for ensuring the favorable nutritional conditions for plants (Tate, 1991).

In spite of a very simple character of the concept of labile and stabile organic matter, differentiation between labile and stable fraction of organic matter, especially in natural conditions, is a very difficult scientific problem. The assessment of the labile pool can be performed by various biological, chemical, and physicochemical methods. A review of these methods is presented in Titova and Kogut (1991). Of special interest is the method of separation of different groups of soil organic matter by the degree of their stability. A scheme has been proposed by Travnikova et al. (1992) based on the models developed by Sauerbeck and Gonzales (1976) and Jenkinson (1990). This scheme takes into account the concepts of physical and chemical stability of organic substances (Figure 3).

However, this scheme ranges different fractions of organic matter not by the degree of their involvement into carbon cycles, but according to their localization within the organic and organomineral fractions.

The most active group of organic substances in soils is the group of partly decomposed fragments of animal and plant residues and microbial biomass. They are not associated with mineral matter; their resistance against degradation is controlled by chemical composition. The rate of mineralization of these substances ranges from several months to several years. The proper humus substances are less active and have a slower rate of renewal. The half-period of decomposition of low-molecular compounds of adsorptive complexes (physically stable humus) is measured in tens of years; high-molecular compounds (not bound with clay minerals) decompose during thousands of years. The most inert matter is represented by coal-like substances. Their resistance against degradation is conditioned by their chemical composition.

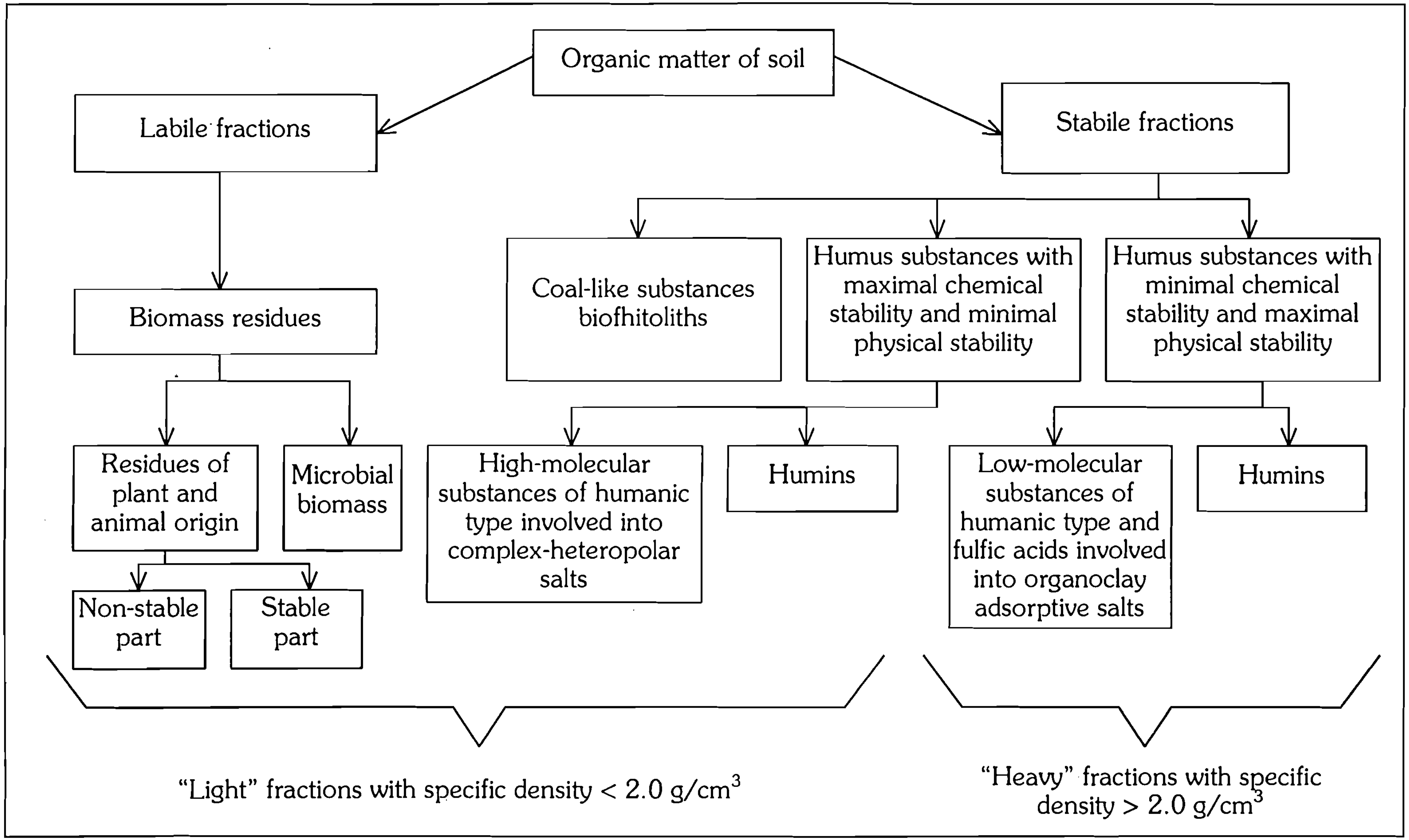


Figure 3. Differentiation of organic substances of soils by the degree of their stability (Travnikova et al., 1992).

Korschens (1992) distinguishes the content of inert (practically, not involved in the carbon cycling at all) carbon (C_i) and easily utilized carbon (C_u). The content of C_i in soils is well correlated with the content of silt and clay particles. It can be determined in the field as the minimal content of carbon, which does not decrease in soils under durable "black" fallow (exposed soil surface) and with no addition of fertilizers. This is the content of carbon that remains in soils after they are depleted of the labile (easily utilized) carbon. A similar approach is developed by D'yakonova (1990).

3.3. Critical Review of the Approaches to Assessment of the Reserves of Organic Carbon in the Soils of Russia

The first attempt of tentative evaluation of the reserves of humus in the main soil types of the USSR was made by Tyurin (1937) based on a relatively small amount of data (Table 3).

In 1947, Bolotina analyzed a considerable amount of experimental data (mainly on the soils of the European part of Russia). Taking into account the results of this work, Tyurin (1949) compiled a new data set on humus reserves in the soils of the USSR (Table 1). Later, this data set was refined and supplemented by data on soils of the agricultural lands of the country, collected by Kononova (1963).

In all above mentioned studies, the reserves of humus were evaluated only for the main types of soils (approximately 11-17 types) that were used for agricultural purposes. The reserves were evaluated in t/ha and no account was made for the total area, occupied by these soil types.

Table 3. The reserves of organic matter in the soils of the USSR (Tyurin, 1937).

Soil	Percent of humus matter in topsoil	Humus reserves, t/ha in the layer 0-100,120 cm
Sierozems	1.0-2.0	50
Light Chestnut (Brown Semidesert	1.5-2.0	100
Dark Chestnut and Southern Chernozems	3.0-4.0	200-250
Ordinary Chernozems	7.0-8.0	400-500
Deep Chernozems	10.0	800
Leached Chernozems	8.0-7.0	600-500
Forest-Steppe Podzolized	6.0-4.0	300-150
Podzolic soils of northern forest zone*	4.0-3.0	120-80
Red-earth, Brown earth, and Podzolized soils of humid subtropics	6.0-4.0	300-150
Mucky-calcareous soils of forest regions	4.0-8.0	200-400
Mountainous Meadow soils**	25	300

Note: * including the litter layer
** soils with high porosity

The total reserves of humus in agricultural soils of the USSR were assessed by Kononova in 1984. However, there were no data on the distribution of humus reserves in soils for different regions of the country (Table 4).

Table 4. The reserves of humus and nitrogen in cultivated soils of the main agricultural areas of the USSR (Kononova, 1984).

Soils	Area under cultivation 10^6 ha	Humus	Nitrogen	Humus	Nitrogen
		t/ha		within the whole area, t·10^6	
Soddy Podzolic	46	53 99	3.2 6.6	2438 4554	147 303
Gray Forest	28	109 215	6.0 12.0	3052 6020	168 336
Leached and Typical Chernozems	56	164 512	9.4 26.5	9184 28672	526 1484
Ordinary and Southern Chernozems	63	137 425	11.3 35.8	8631 26775	712 2255
Dark Chestnut and Chestnut soils	21	99 229	5.6 13.8	2079 4809	1176 2898
Sierozems (under irrigation)	8	40 83	2.5 7.5	320 664	20 60

This gap was filled only recently in the work of Orlov and Biryukova (1995) (see Table 2). In this study, a broad diversity of soils is considered (more than 70 types). The data were collected for the soils of each of the eight natural-agricultural zones of the country, as well as for mountainous and plain regions. However, there is no data on the storage of carbon in the litter layer of soils, though, as it was shown by Cherkinskii and Chichagova (1992), the main part of carbon in some soils is contained in litter (especially, in soils of humid boreal landscapes). Also, the authors have not made special allowance for the content of coarse rock fragments in soils. And, finally, as well as in most of the studies on carbon reserves in soils, the assessment has been performed only for a top layer of one meter. Actually, for many soils this "reference depth" is quite reasonable. However, a soil profile may have a greater depth, and a high activity of soil biota may be observed in deeper layers. Therefore, Cherkinskii and Chichagova (1992) suggested that the "reference" depth of organic profiles of soils should be set to 90-95% of the total thickness of the reserves of organic matter. Our calculations suggest that the top meter thickness of deep Chernozems only contains 80-85% of the total reserve of carbon in these soils, whereas the layer 0-200 cm contains more than 95%. Therefore, a "better" reference depth is two meters.

Finally, it should be noted that for comprehensive studies of the carbon budget in soils, it is necessary to evaluate not only the reserves of organic carbon, but also the reserves of carbon in carbonates. The work of Glazovskaya (1996) clearly shows the great role of pedogenic carbonates in the total reserves of carbon in steppe, semidesert, and desert soils, especially, if deep soil profiles are analyzed. And surely these data should be combined and analyzed together with the data on hydrochemical discharge of substances from a particular territory. Another serious problem in the calculations is the problem of the assessment of the reserves of lithogenic carbon of soil carbonates.

Summarizing the available data, we can conclude that at present there are no assessments of carbon reserves in the soils of Russian Federation that take into account modern cartographic materials and are supported by extensive databases. Most of the data present the assessment of just organic-bound carbon, without making the distinctions between different groups of organic matter in soils.

The work of Orlov and Biryukova (1995) does not account for the carbon stored in litter layers. No allowances are made for the stoniness in soils and for a certain inconsistency in the methods of carbon determination. Finally, there were no attempts to compute the reserves of carbonate-bound carbon for the whole country, although the significant role of these compounds in carbon cycling has been vividly shown by Glazovskaya (1996).

It is obvious that in order to achieve satisfactory results applicable in modeling studies of carbon cycling, it is necessary to overcome these difficult problems.

The authors believe that this study will partially fill in the gaps in our knowledge on the carbon storage in soils and will allow us to move to the next stage, namely the elaboration of models, describing the carbon sequestration in the main terrestrial reserves of carbon compounds.

4. Principles and Methods for Generation of a Map of the Carbon Content in Russian Soils

4.1. Methods and Principles for Calculations of the Organic Carbon Pools

During the last 4-5 decades, the major method for determination of the carbon content in Russian (Soviet) mineral soils was the wet combustion method suggested by Tyurin (1937). It is an indirect method. The method does not determine the proper soil organic carbon, but detects the oxidation degree of organic matter. Moreover, chromous mixture used in the method does not provide a complete combustion of soil organic matter. It is especially true for the samples of the top horizons of forest soils containing slowly decomposable fragments of plant residues and peat which cannot be removed by simple treatments. The Tyurin method has proven to determine 85-90% of the organic carbon determined by dry combustion (Bel'chikova, 1975; Orlov and Grishina, 1981). A method developed by Walkley-Black, similar to the Tyurin method, is widely used in other countries.

Numerous attempts have been made to establish transition coefficients for different methods. In the literature, the following coefficients have been suggested to recalculate the data of the dichromate method by Walkley-Black into dry combustion results: 1.24, 1.32 (Gillman et al., 1986), 1.33 (Bornemisza et al., 1979), 1.41 (Amacher et al., 1986). A generalized coefficient of 1.28±0.19 was suggested for the recalculation of organic carbon content determined by the Tyurin method to that determined by dry combustion in automatic equipment (Kogut and Frid, 1993). Special methodical investigations were carried out by the authors of this report for standard soil samples and the following recalculation coefficients were suggested for different soils: typical chernozem 1.13; soddy-podzolic soil 1.30; light chestnut soil 1.26; leached chernozem 1.23; calcareous chernozem 1.29; salinized soil 1.34; solonetzes 1.32.

For other soil types, recalculation coefficients were chosen from those of genetically similar soil types, or a general coefficient equal to 1.28 was used.

The pools of air-dried peat were recalculated into burning materials (the mineral part was considered) and then into organic carbon pools. We assumed that the average carbon content was 56% in upland peat and 58% in lowland peat (Lishtvan et al., 1989). The same way of peat recalculation was used in the work of Orlov and Biryukova (1995).

The pools of air-dried litter material were recalculated into organic carbon pools in the same way. The average carbon content was assumed to be 56% in the O1 horizon of forest litter and 38% in the O3 horizon. When data on the biomass pool of the subhorizons were not available, an average percentage of 48% of organic carbon content in the litter was used.

The calculation of the organic carbon content in the organic matter of litter subhorizons was based on the data obtained by Lebedev and Zolotukhina (1989). The authors determined the organic carbon content in litter samples by the Tyurin method modified by Nikitin. We suppose that the direct carbon determination by dry combustion would give higher values. As empirical coefficients of the transition from the Tyurin method to dry combustion are missing, a conditional coefficient of 1.2 was applied.

4.2. Assessment of the Bulk Density of Soils, the Content of Stones, and the Content of Coarse Organic Fragments (Roots, Branches, etc.)

Since the very first study by Tyurin (1937), the problem of assessing the bulk density of soils, for computing the reserves of humus is one of the main obstacles for scientists. Unfortunately, this important characteristic is usually missing in studies considering the humus content in the soils. Usually, some average values are used and no distinction is made between the soils, belonging to the same type, but characterized by different texture.

In this study we tried to solve this problem by assigning different values on the soil bulk density to the soils of different textural classes. Roughly, all the soils were divided into three groups: "sandy," "loamy," and "clayey." If a certain soil type (e.g. typical chernozem) can be found in all the groups, it would be characterized by different bulk density values, specific for each group.

The initial data on bulk density was collected from numerous sources, used in the database compilation. All the data in the database can be divided into three types: (a) single determination, (b) statistical assessment of a certain type of soil, and (c) expert estimate.

Most of the initial data belong to the first two groups. A valuable source of information on the bulk density of soils in different regions of the country was found in the four-volume monograph "Agrophysical characterization of soils of the USSR," issued in the 1970s and 1980s.

For most of the soils of plain territories of the country, the data on bulk density can be considered as quite accurate. The main problems arose with soils of mountainous regions.

Only a few publications exist where the calculations of the bulk density are made separately for fine earth fractions and for the whole volume of soils including coarse fragments.

To account for the content of coarse mineral fragments (soil stoniness) in the soils of mountain regions formed on hard rocks, it is necessary to collect data on the content and profile distribution of stony material in the soils. Unlike the assessment of bulk density, mostly based on factual data, the assessment of the stoniness in soils is largely expert estimates. The average depth of soil profiles in mountainous regions (differentially for different soils types) was taken into account. It was assumed that in most cases the depth is restricted by a high content of skeletal material (rock debris), i.e. the stone content at the lower depth of soil profile was assumed to be equal to 90-100%, whereas in the upper part of the soils it usually does not exceed 20-30%. As for the territories with bedrocks, an additional correction for the content of stones was made directly from the map, where such areas are specially marked. An extensive field experience by the authors of this report in different regions of the country, especially in the Central Siberia, where the percentage of stony soils is very large, allows us to consider the expert evaluations as quite accurate.

Unfortunately, at this stage it was impossible to assess properly the content of organic coarse fragments (roots, branches. trunks, etc.) in soils. The main difficulty is that such an assessment would require a precise correlation between the map of vegetation (including anthropogenic modifications) and the soil map. This would inevitably result in a serious complication of the generation of the final map (soils + vegetation) and make the task of assessment of carbon reserves much more difficult.

In current methods of carbon estimation in mineral soils, root residues are not taken into account and in order to gain an overall assessment of the carbon stores in soils (including roots) one should sum up the data on carbon stores in mineral soils with the data on "underground vegetation." The correction of data on the bulk density for the content of organic coarse fragments does not seem as important as the stone content, even in forest biocenoses (for the mineral part of the soil profile). The methods of carbon estimation of organogenic horizons (litter, peat) allow us to have direct data on the reserves of carbon in the horizons, including fine roots, small branches, needles, leaves, etc. Therefore, this part of the organic-bound carbon is included in our database.

5. Map of Carbon Reserves in the Soils of the Russian Federation

5.1. General Description of the Map

The map of carbon reserves was generated from the 1989 soil map of Russia in the scale of 1:2.5 million and from the map of Russia and neighboring territories in the scale of 1:4 million (Gerasimova et al., 1995). The generalization was performed on the basis of the digitized map of soil-geographical regionalization of the USSR in the scale of 1:4 million (Dobrovol'skii et al., 1984).

It should be mentioned that the soil map and the map of soil-geographical regionalization have been compiled independently; there are inconsistencies in the position of the borders of soil contours, especially in mountain regions.

The legend of the initial soil map includes approximately 160 soil types and complexes and 9 types of parent materials forming 16 combinations at the map.

Based on published information, we created the humus profiles of all soil types denoted at the map. Only soils which are not found at the territory of Russia were excluded (sierozems and ferrallitic soils).

For every soil type, several representative profiles are represented in the database, considering soils with various texture. Based on that, it was possible to choose a convenient profile for every map contour, except for soil complexes.

To estimate the humus pools of soil complexes, an expert estimation of the percentage of the different soils in a complex was made. An average weighed pool was then assigned to a complex contour.

The method of humus pool calculation via humus profile is simple and can be restricted to a numeric integration by a rectangular method. The following values are thus considered:

1. Humus content, %;
2. Volume weight of a horizon, g/cm^3;
3. Stone content, %.

The information about volume weights and stone content was obtained from the literature and included into the humus profile database.

The following information was included into a resulting map:

1. Pool of organic carbon in the layer 0-20 cm, t/ha;
2. Organic carbon in the layer 0-50 cm, t/ha;
3. Organic carbon in the layer 0-100 cm, t/ha;
4. Inorganic carbon in the layer 0-100 cm, t/ha;
5. Total organogenic carbon, t/ha;
6. Thickness of organogenic horizon, cm.

The final map contains about 7000 contours, resulting from the generalization of neighboring soil contours with the same humus profiles. As the humus content values are stored in the same way they were calculated, the generalization could be conducted only by texture. Texture generalization was required in cases with insufficient published information about volume weight and stone content, and in cases lacking information on additional soils. The latter resulted from the absence of information at the map about the percentage of additional soils in the contours. Thus, it was impossible to calculate an average weighted carbon content including additional soils.

The calculations and assessments of carbon reserves were performed with the use of ARC/INFO.

5.2. General Results

Due to the big volume of the initial database and computed data on carbon reserves in different soils, a certain generalization of the results obtained was required. This generalization was performed on the basis of the digitized map of soil-geographical regionalization of the USSR in the scale of 1:4 million (Dobrovol'skii et al., 1984).

Table 5 presents the data on carbon content within the regions, delineated on the map of the soil-geographical regionalization (for the territory of the Russian Federation), without differentiation by different soil types. More detailed information on carbon reserves in different soil types is given in the Appendix.

Table 5. Carbon reserves in the soils of the Russian Federation (generalized data).

Soil Zone	**Total Area, thous. ha**	**The Reserves of Organic Carbon by Soil Layers, million tons***				**Carbon of Carbonates, million tons**	**Total Carbon, million tons**
		0 - 5 cm	**0 - 20 cm**	**0 - 50 cm**	**0 - 100 cm**	**0 - 100 cm**	**0 - 100 cm**
Zone of arctic soils (Arctic tundra and Polar desert)	**2378**	30.9 11.9	85.1 27.3	119.9 27.3	**130.3** **27.3**	107.3	**237.6**
Zone of tundra humus illuvial soils (Subarctic tundra)	**132490**	4016.8 3041.8	15189.9 11671.2	28828.7 20964.9	**39662.7** **28274.3**	1653.5	**41316.2**
Zone of gley podzolic and podzolic humus illuvial soils (Northern Taiga)	**127280**	5647.4 4258.2	15750.8 9640.1	26961.5 12931.2	**36686.4** **17331.4**	487.7	**37174.1**
Zone of podzolic soils (Middle Taiga)	**110663**	4100.0 2981.0	10547.8 6392.0	16913.4 7712.7	**22210.2** **9777.6**	465.3	**22675.5**
Zone of soddy podzolic soils (Southern Taiga)	**157513**	3989.4 2043.8	11271.7 4379.6	17142.1 5539.5	**22443.2** **7373.1**	153.1	**22596.3**
Zone of gley frozen soils (Northern Taiga Permafrost-affected)	**86000**	2262.4 1267.1	8940.1 3432.7	15283.9 5429.9	**21661.3** **8230.4**	9703.8	**31365.1**
Zone of frozen taiga soils (Middle taiga Permafrost-affected)	**96268**	3287.1 2028.0	8661.3 2802.1	13719.5 3325.0	**18217.6** **4247.0**	17299.8	**35517.4**
Zone of forest ash-volcanic soils (Taiga zone of Kamchatka)	**8892**	410.0 340.8	1071.2 589.5	2637.4 1045.7	**4816.2** **1848.4**	0.2	**4816.4**
Zone of podzolic and brown forest soils	**21295**	833.4 657.9	2705.9 1493.2	5086.8 2338.3	**7467.2** **3720.0**	4.2	**7471.4**
Zone of brown forest soils (South Taiga)	**16541**	411.1 88.1	1291.4 249.8	2300.4 590.3	**3361.8** **1122.3**	282.9	**3644.7**
Zone of gray forest soils, podzolized, leached, and typical chernozems) (Forest-Steppe and Northern Steppe)	**130018**	2577.0 361.8	9475.5 738.9	18207.3 1125.0	**25787.8** **1728.3**	11695.4	**37483.2**
Zone of ordinary and southern chernozems (Steppe zone)	**65290**	1266.2 20.4	4879.5 53.1	10118.0 114.6	**14385.4** **210.7**	20596.7	**34982.1**
Zone of dark chestnut and chestnut soils (South Steppe and Dry Steppe)	**26254**	387.4 3.3	1414.6 3.4	2765.1 3.4	**3789.0** **3.4**	13365.8	**17154.8**
Zone of light chestnut and brown semidesert soils (Dry Steppe and Semidesert)	**16845**	172.9 20.8	596.5 20.8	1067.2 20.8	**1387.2** **20.8**	8797.3	**10184.5**
Zone of red and yellow ferrallitic soils (Wet Deciduous Forests)	**6**	0.2 0.0	0.5 0.0	0.6 0.0	**0.7** **0.0**	0.0	**0.7**

Zone of sierozemic soils (Semidesert Foothill landscapes)	**129**	1.2 0.8	3.9 0.8	6.7 0.8	**8.6** **0.8**	44.0	**52.6**
Total for the soils of plain territories	**997862**	29393.4 17125.7	91885.7 41494.5	161158.5 61169.4	**222015.6** **83915.8**	84657.0	**306672.6**
Mountain tundra and mountain arctic soils (Mountain Tundra)	**81537**	1853.1 1465.9	6517.2 4347.1	11292.6 5928.2	**13450.8** **6733.5**	1007.3	**14458.1**
Mountain podzolic humus-illuvial soils and mountain tundra soils (Mountain Tundra and Northern Taiga)	**1167**	81.4 73.2	239.2 131.8	398.4 134.3	**488.5** **138.2**	0.0	**488.5**
Mountain podzolic, mountain meadow, and mountain tundra soils (Alpine Tundra and Alpine Meadows)	**15749**	376.0 162.1	1011.8 272.8	1467.1 283.3	**1777.8** **299.7**	0.7	**1778.5**
Mountain gley frozen taiga, mountain tundra, mountain cryoarid, and mountain steppe soils (Mountain Permafrost-affected Continental Landscapes)	**183824**	4783.4 2636.1	13741.8 5743.8	23186.5 6935.3	**29902.2** **8336.5**	11653.0	**41555.2**
Mountain frozen taiga and mountain tundra soils	**173170**	5497.4 3029.1	14576.3 5969.3	25542.9 7236.1	**33080.5** **9467.7**	8277.3	**41357.8**
Mountain soddy taiga, soddy podzolic, frozen taiga, podzolic humus-illuvial, and tundra soils	**47694**	1258.0 648.8	3217.3 1080.8	5491.6 1385.3	**7272.8** **1921.8**	1996.6	**9269.4**
Mountain forest ash-volcanic and mountain tundra soils (Mountain Forest and Tundra Volcanic Landscapes)	**15819**	559.3 437.6	1309.9 664.4	2452.3 742.9	**3921.6** **818.2**	3.4	**3925.0**
Mountain podzolic and mountain tundra soils	**23199**	969.3 865.9	3241.4 2204.2	6019.6 2408.9	**7212.9** **2572.6**	231.3	**7444.2**
Mountain brown taiga humus-illuvial and mountain tundra soils	**45839**	1864.3 1250.3	5209.1 2223.8	9181.3 2705.1	**11886.0** **3494.1**	276.2	**12162.2**
Mountain chernozems, mountain brown forest, and mountain meadow soils	**5420**	31.3 7.4	442.0 7.4	703.9 7.4	**872.4** **7.4**	518.4	**1390.8**
Mountain chestnut, mountain brown forest, and mountain meadow soils	**1025**	28.9 1.7	96.9 1.7	136.9 1.7	**149.0** **1.7**	0.0	**149.0**
Mountain chernozems, mountain gray forest, and mountain meadow soils	**50312**	1261.1 485.9	3522.8 671.0	5684.7 671.0	**7182.2** **671.0**	2568.8	**97510.0**
Mountain brown forest, mountain podzolic, mountain meadow, and mountain tundra soils	**15741**	483.0 206.8	1444.4 352.4	2107.8 440.9	**2617.1** **579.1**	10.4	**2627.5**
Mountain meadow-steppe and mountain steppe soils	**1217**	23.5 0.8	67.5 0.8	87.3 0.8	**97.7** **0.8**	76.3	**174.0**
Mountain yellow and red ferrallitic, mountain brown forest, and mountain meadow soils	**778**	23.2 2.2	77.0 2.2	110.6 2.2	**126.2** **2.2**	0.0	**126.2**
Mountain chestnut, mountain cinnamonic, mountain chernozemic, and	**241**	7.2	24.0	33.3	**35.2**	2.1	**37.3**

mountain meadow soils		0.3	0.3	0.3	**0.3**		
Total for the soils of mountain areas	**662732**	19100.4 11174.1	54738.6 23673.8	93896.8 28883.7	**120072.9** **35544.8**	26621.8	**146694.7**
Total for Russia	**1660594**	48493.8 28299.8	146624.3 65168.3	255055.3 90053.1	**342088.5** **119460.6**	111278.8	**453367.3**

Footnote: Numerator — total reserves of organic carbon; denominator — the reserves of organic carbon, accumulated in organogenic horizons (peat and litter) with carbon content > 15%.

The important distinctions of the results presented in Table 5 from previously obtained results are as follows:

(a) For the first time the calculations have been performed on the basis of a digitized soil map with detailed information on soil cover features, including the spatial heterogeneity of soil cover contours. Computerized technologies were applied to area assessment, which enabled to calculate the areas, occupied by a particular soil with a great detail. Not only homogeneous soil contours were taken into consideration, but also the shares occupied by particular soils within heterogeneous soil contours (soil complexes) were accounted for. It was possible to take the areas occupied by inland waters and large bedrocks into account. Therefore, the total area assessed as presented in Table 5 (16.6 million km^2) is somewhat lower than the official data on the area of Russia (17.1 million km^2).

(b) The database compiled allowed to perform various calculations of the reserves of carbon within the two-meter depth of soils. However, in this case the preference was given to four major layers: 0-5 cm (mainly, organogenic horizons, forest litters, the upper part of humus horizon with the most labile organic forms of carbon); 0-20 cm (approximately corresponding to arable layer in cultivated soils which is important for the assessment of the reserves of humus-bound carbon); 0-50 cm (representing the reserves of carbon within the layer of maximum root abundance; the carbon content in this layer is also very characteristic for shallow soils, permafrost-affected soils, and mountain soils); and 0-100 cm as the most important reference layer, for which the greatest amount of data is available in the world literature.

(c) The data on concentration of organic-bound carbon in mineral horizons of soils were corrected for the method of carbon estimation (see Section 4.1).

(d) Together with the data on humus-bound carbon, the reserves of carbon in organogenic horizons have been assessed. Thus, the data on the total reserve of organic carbon includes not only the carbon stored in mineral soil layers, but also the carbon of forest litters, steppe, and peat layers. Special consideration on the carbon of organogenic horizons seems very important in the context of evaluation of the lability of soil carbon pool.

(e) The assessment of carbon reserves is made with due account for the data on bulk densities of soils (heavy-, medium- and light-textured soils have been considered separately), and for the content of stony material, which is especially important for the soils of mountainous regions.

(f) For the first time an attempt is made to evaluate the reserves of carbonate-bound carbon in the soils of the Russian Federation. Since the amount of collected primary data on concentration of different forms of carbonates in soils (carbonates of rock fragments, lithogenic (inherited) carbonates, proper pedogenic carbonates) is insufficient for correct evaluations, the presented data should be considered as tentative and rough estimates of the reserves of carbonate-bound carbon in soils. However, the calculations show the great role of this reserve of soil carbon, which is often underestimated in the literature.

Although the methods for data calculation and the databases used by us are different from those used in the work by Orlov and Biryukova (1995), the results obtained show agreement.

The total reserve of organic carbon in the one meter layer of the soils of Russia is estimated by us to be 342.1 billion tons, of which 119.5 billion tons of carbon are accumulated in the organogenic horizons. The reserve of carbonate-bound carbon constitutes 111.3 billion tons, and the total reserve of mineral and organic carbon amounts to 453.4 billion tons. These data testify the importance of the assessment of the carbonate-bound carbon, which comprises about 25% of the total reserve of carbon. The share of mineral forms of carbon progressively increases down the soil profile.

The assessments of the reserves of organic carbon in the soils of plain territories, obtained by us respectively by Orlov and Biryukova (1995) are very similar, in spite of different methods of calculation (222.0 billion tons and 236.2 billion tons, correspondingly). However, the data on the reserves of organic carbon in the soils of mountainous regions substantially differ (120.1 billion tons and 60.0 billion tons, correspondingly). This difference can be explained by the difference in the original database. In our database, all types of soils that occur in the mountain soils are considered, whereas in the work of Orlov and Biryukova only data for a number of types of specific mountain soils were used.

It is interesting to note that about 35% of the total reserve of the organic carbon in the soils of Russia is composed of carbon, accumulated in litter and peat horizons. The difference between natural zones concerning the share of carbon of organogenic horizons is especially well expressed. Thus, within the zones of subarctic tundra and taiga, carbon of organogenic horizons accounts for 30-50% of the total amount of organic carbon, whereas within the steppe zone of chernozemic soils it constitutes no more than 1-2%.

More detailed data on carbon reserves in different types of soils and within different zones is included in the Appendix.

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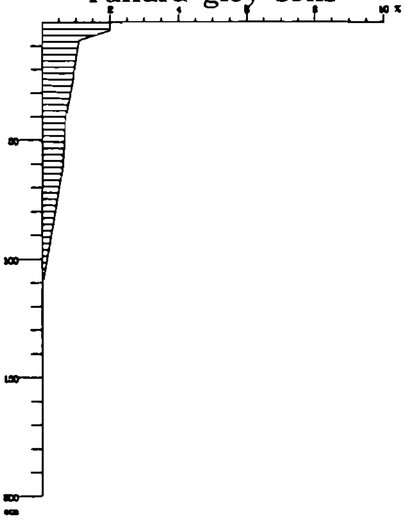
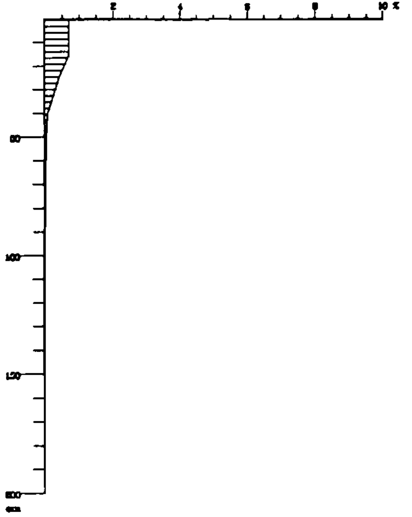
Appendix 1. Schematic maps of the reserves of organic carbon within the soil layers expressed in tons/ha: 0-20, 0-50, and 0-100 cm.

Appendix 2. Humus profiles of typical soils.

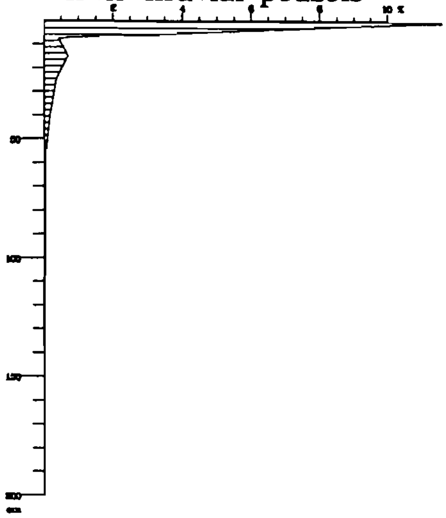
Humus profiles of typical soils



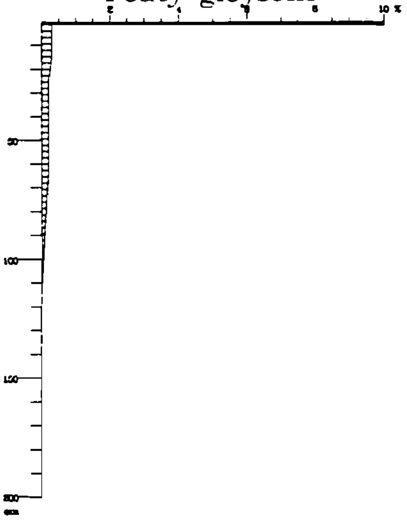
Tundra gley soils



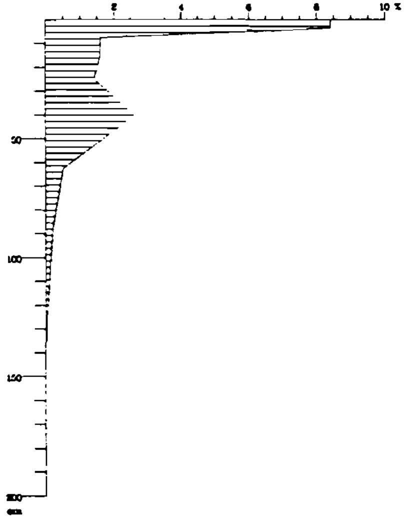
Podzolic soils



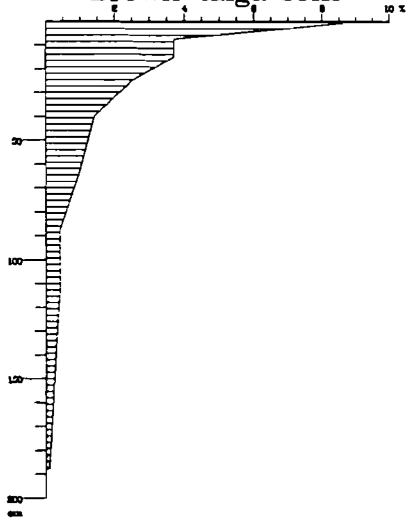
Iron-illuvial podzols



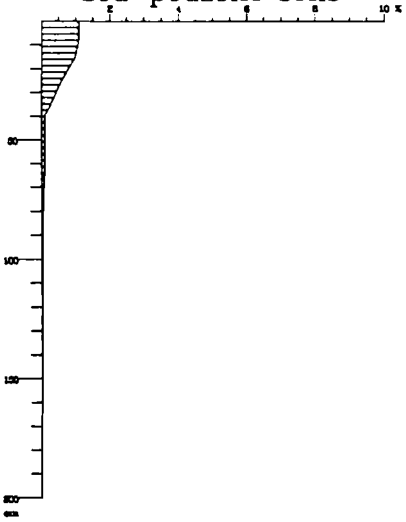
Peaty gleysoils



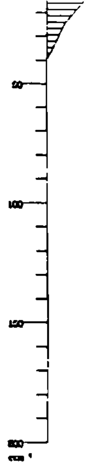
Podburs



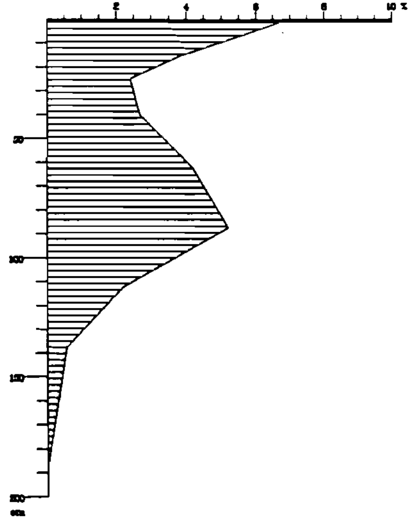
Brown taiga soils



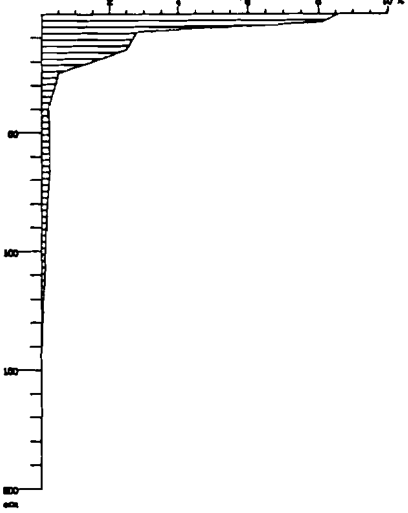
Sod-podzolic soils



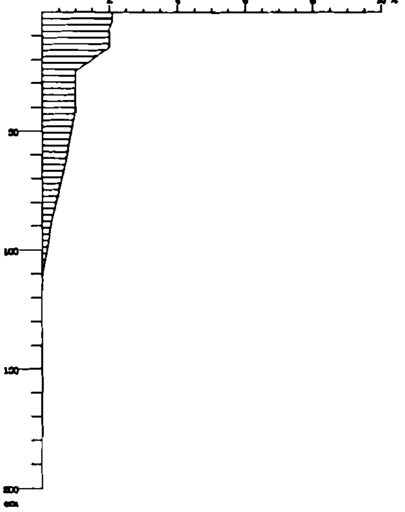
Sod-podzolic gley soils



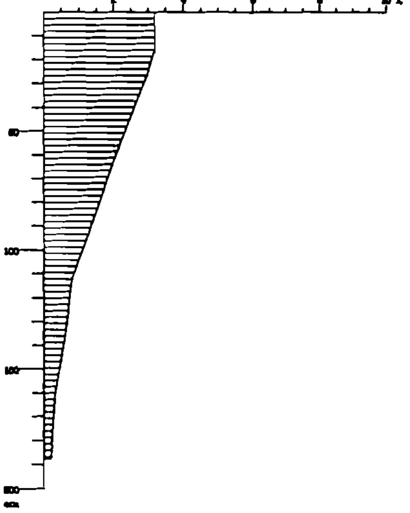
Volcanic ochric soils



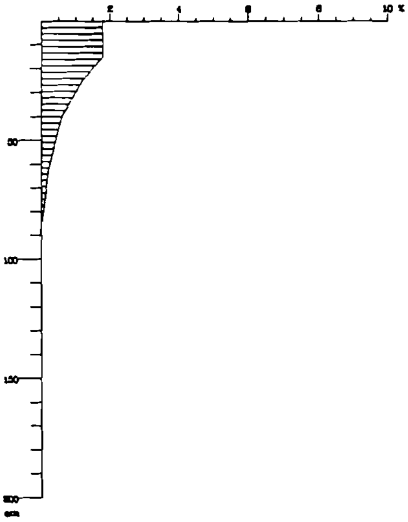
Brown forest typical soils



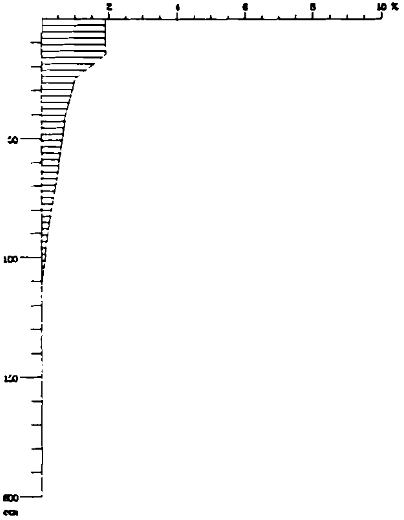
Grey forest soils



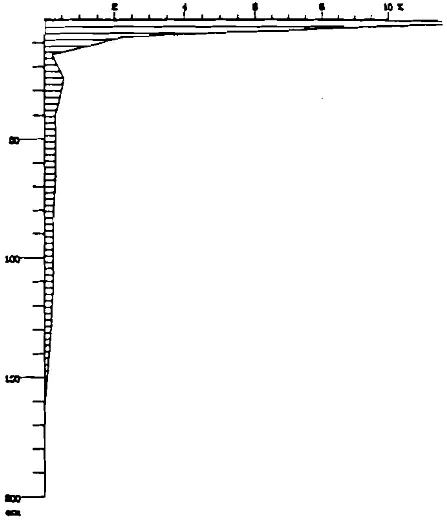
Typical chernozems



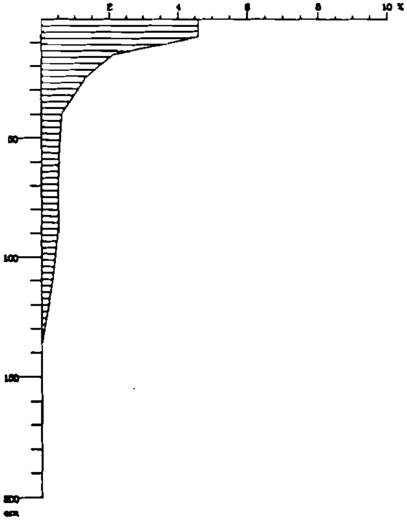
Chestnut and dark-chestnut soils



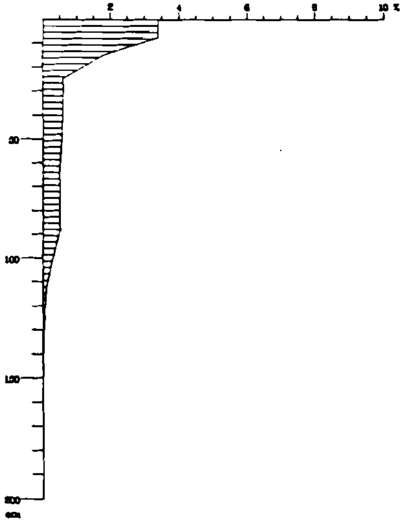
Meadow-chestnut soils



Solods



Solonetzs



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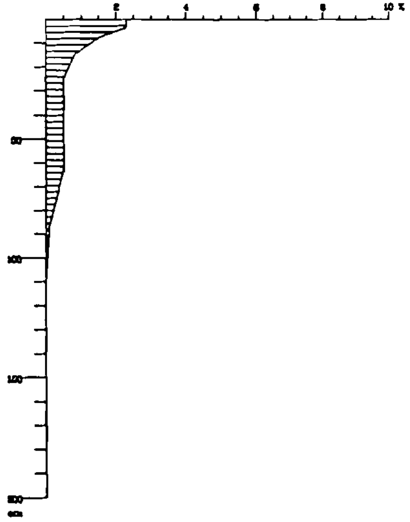

Sod alluvial soils