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Soils

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This study attempts an assessment of the global changes in soil wrought by human action over the past 300 years. This task is by no means simple for a number of reasons. Order must be made of the great variability in soils across the earth, and distinctions must be made between natural and anthropogenic soil changes at varying space and time scales – past and current changes, global and local changes – and between reversible and irreversible changes, again at varying scales. Moreover, because of the woeful gaps in the data, both spatial and temporal, and the paucity of work of this kind, a global assessment requires generalization of a high order.

A full analysis can be achieved only through a step-by-step approximation procedure, *bearing in mind the extreme scarcity and unreliability of the existing global and even local quantitative data*. Many of the "data," especially at the global scale, are a product of estimation and not the result of actual measurement. Estimates typically are produced by the application of a "constant" of change to general soil types and groups, and as a result, they can vary greatly with a change in the constant used. At the present stage of our efforts, it is impossible to avoid the controversy that is inherent in providing global estimates and generalizations. Our effort, however, provides an initial, if rudimentary, assessment, and points to the areas in which future research is especially needed, including the development of estimation methods.

Soil As a Subsystem of the Biosphere

Soil is not only a productive layer of the earth's surface; it is a "natural" body with regular structure and specialized features, a subsystem within the ecosystem or geosystem. The soil cover, or pedosphere, is a zone of interaction at the elusive boundary of the biosphere and geosphere. It is not only a simple friable layer and a stock of plant nutrients at the land surface, but also a specific membrane, regularly differentiated in space and depth, that regulates biosphere-geosphere interactions. The pedosphere is a part of the lithosphere, and is also penetrated and saturated with elements of all of the other geospheres: gases, water, solutions, and micro-, meso-, and macrobiota. Both soil as a natural body and the pedosphere as a surface geomembrane are systems with their own laws of development, evolution, stability, and behavior, which constitute a very complicated set of direct and indirect links with surface processes, both natural and anthropogenic.

Soil Formation

Soil is formed and developed as a structure of dynamic equilibrium with a firm framework in the upper lithosphere as a result of continuous ($n \times 10^2 - n \times 10^5$ yr) atmospheric, hydrospheric, biologic, and geologic processes. In a narrow and precise sense, soil formation is a result of accumulation *in situ*, at specific points, of solid-phase products of the continuous functioning of the biosphere. In a broader sense, soil formation occurs in combination with lithogenesis, as in the case of fluvigenic, eolian, and volcanically transported sediments. Soil may show radical changes from the original attributes of parent rocks, accumulate fertility, and become a component of the environment for living organisms. It is a powerful regulator of further functioning of ecosystems, as well as affecting many flows of matter and energy on the land surface. Thus, soils are simultaneously products of the functioning of the biosphere and the upper lithosphere, and necessary components and regulators of the operation of the entire terrestrial surface system. In light of these considerations, the study of soil change must involve the changes in the solid-phase framework of the soil body, accumulating the products of and changes in the functioning of the soil as a multiple-phase system with a set of current biospheric processes.

Studies of these attributes of soils and the estimates that will result are considered by some soil scientists to be of top priority. The data that have been accumulated in this direction are rather fragmented, controversial, and often unreliable. As a result, it is virtually impossible to undertake such a program in detail at this time, although the general structure for such a program is offered. In addition, we suggest certain trends in soil change under the impress of human action over the past 300 years, recognizing that the overall changes in the pedosphere have also been affected by natural factors. As a rough approximation, we assume that the largest part of the pedosphere is in a state of quasi-equilibrium with the environment; that is, it is either in a state of gradual evolution synchronous with the natural evolution of climate, topography, and biota, or in a state of reversible fluctuations adequate to short- and medium-term fluctuations of climate and other factors.

Soil Functions in the Global System

Our assessment of the global soil changes induced by human action begins with the functions served by soil in the geosystem and particularly in the biosphere. The first and the main function is to support life. During soil formation, minerals essential to organisms are concentrated in the available forms of chemical compounds. Soil provides the primary producers of terrestrial ecosystems with a steady supply of minerals, nutrients, and water. It is a home for plant roots and is inhabited by a multitude of small animals and microorganisms.

The second important soil function is the maintenance of sustainable interaction between the great geological and the small biological turnovers of substances on the earth's surface. It is through the soil that biogeochemical cycles of elements, including the crucial ones of carbon, nitrogen, and oxygen, are performed.

The third function of soil lies in the regulation of the chemical composition of the atmosphere and hydrosphere. Due to its porosity (up to 60% of its volume) and its dense population of soil organisms, soil constantly is exchanging different gases with the lower atmosphere; it absorbs oxygen and evolves carbon dioxide. What is known as "soil respiration" supports, together with the direct photosynthesis and respiration of organisms, the stable composition of near-surface air. Soil also absorbs or evolves such gases as methane, ammonia, hydrogen sulfide, carbohydrates, nitrogen oxides, and various organic gaseous compounds. Because of its physicochemical exchange capacity and its specific hydrophysical features, soil selectively discharges water-soluble chemical compounds or ions into surface and underground water flows, thus affecting the hydrochemical state of the continents and the coastal areas of the oceans.

The fourth soil function is the regulation, along with climatic regulators, of biospheric processes, particularly the density and productivity of organisms on the earth's surface. Soil properties in a given climate limit the activity of particular plant and animal species.

The fifth and final function is the accumulation of active organic matter, or soil humus, and the energy bound to it, at the earth's surface. Organic matter, especially in the warmer and more humid environments, is quickly destroyed and mineralized soon after the death of an organism. A certain part of it is transferred into the soil humus and preserved.

These functions of soil vary greatly under human impacts, which can be either intentional or unintentional, and direct or indirect. Soil functions in the future may be divided between those of soil as a "natural" or physical body and soil as a geomembrane, analogous in some ways to a biomembrane, which regulates interactions between the internal and external earth spheres. While soil science has accumulated a relatively large body of knowledge in regard to the former division, the latter is in its infancy of study and understanding. The very concept of soil as a geomembrane needs definition and development. It would seem useful to include within the concept the capacities to reflect, absorb, or admit selectively and to transform substances and energy flows between the internal and external earth spheres.

Specific to human needs, soil is a vital resource, critical to food production and to forestry and important to settlement in general. These roles are so well known that they need not be reiterated here; more important to this discussion are the impacts upon soil of these and other human uses.

Human Impacts

In the analysis of human or anthropotechnogenic impacts (henceforth referred to as ATIs) and corresponding soil changes, a sequence of types may be identified. Here we identify five types, ranging from the slightest to the strongest impacts.

In the *first type*, human action has changed certain unstable components of the environment, while the basic structure of the whole ecosystem remains unchanged. Regions that display this ATI tend to be the most ecologically hostile to, and typically the most remote from, human settlement, such as the arctic and subarctic tundra, and some mountain forests, swamps, and the like; and they comprise about 39% of the land area of the earth. Certain slight and relatively "harmless" anthropogenic changes in atmospheric and hydrospheric components of these ecosystems have taken place, as have some consequent changes in soil functioning (including the results of pollution and acid rain), but not yet in the soil body.

In the *second type*, human-induced changes have occurred in the biota, while changing the soil only marginally. These ATIs are found in rangelands, pastures, and meadows, comprising about 20% of the global land area. Certain naturallike processes of soil evolution, usually of degradation, can occur following changes in biota, such as soil erosion, dehumification, loss of structure, and compacting. These processes may be combined with the changes characteristic of the first type of ATI. It must be recognized that radical changes in biota can have significant impacts on rangelands and that the impacts of any class of changes vary by broad climatic zones (such as tropical versus midlatitude grasslands).

The *third type* is the most important for humankind. This is the ATIs affecting arable land, comprising about 10% of the global land area and occupying the most productive soils of the pedosphere. In this type, soils are exposed particularly to highly complex and diversified impacts and changes.

The *fourth type* takes place in ecogeosystems that have been severely damaged or destroyed by human activity up to the state of sterility. In such landscapes, the structure of the entire ecosystem and soil body is destroyed, and the principal remaining processes are abiotic or almost abiotic, in some cases resulting in bare rock outcrops, badlands, shifting sands, and desert pavements. The extent of the total global area thus affected in the history of humankind is a highly speculative and controversial matter. Some authors (Dobrovolsky and Urusevskaja 1984; Kovda 1981; Ryabchikov 1972) believe that much of the area of such landscapes, perhaps 7% of the world's land, is of anthropogenic origin. Other scholars would find this figure excessive and claim that relatively little of the land now entirely unusable for productive activity has been rendered so by human action.

The *fifth type*, which occupies about 6% of the earth's land surface, involves landscapes also radically changed, but for productive human uses, such as settlement, roads, and reservoirs. Such withdrawals are necessary, as human populations require land on which to live, but they often have been excessive and irrational.

The last two types of lands affected by anthropogenic processes up to the extent of almost total loss of their original productivity make about 13% of the world's land. This constitutes an area larger than that of the present arable land. Remembering that these estimates are controversial, we suggest that large fractions of the world land surface have been damaged in such major ways as to be basically useless for agriculture (crops and livestock), constituting an area about the size of Africa. The effects of these impacts are illustrated in the following world estimates: (1) about 15 million km^2 of land (nearly 10% of the global land area, and larger than Antarctica) are under permanent cultivation at present; (2) about 20 million km^2 (an area larger than South America) of formerly productive land were irreversibly lost, whether transformed into badlands and deserts or covered with water, buildings, or asphalt pavements in the past 10,000 years of agricultural civilization; (3) about only 10 million km^2 (approximately the area of Europe) of land suitable for agriculture remain as an arable land reserve of human development, being scattered in small patches throughout the continents and occupying more or less larger areas in savannas and forests of Africa and South America; and (4) today's annual irreversible loss of productive land amounts to 60 to 70,000 km^2 (the area of Sierra Leone), a rate 30 to 35 times higher than the average historical losses for the 10,000-year period.

It is necessary to emphasize that all of these ATIs are closely interconnected in space and time, and may be combined with one another in various ways, producing unexpected synergistic and emergent effects. ATIs in reality, moreover, are much more complicated than this rather simplified typology would suggest. In general, it may be said that the nature of the pedosphere itself tends to produce a so-called lump or patchwork pattern, one of extremely high lateral heterogeneity of the soil cover at all levels and scales. This natural diversity has been significantly overlain for more than 10,000 years, and with particular intensity for the past 300 with very complex ATIs that change sharply and rapidly in type, strength, and depth over time and space. For the pedosphere as a whole, consequently, it would be virtually impossible to distinguish one principal or leading tendency of change over the past three centuries. *What can be positively stated is that within this period, the total area and quality of productive soils available for human and biotic use has decreased at an accelerating speed.* In all other respects, we see a multitude of varying soil changes produced by the diversity of the pedosphere. Both the natural soil geography and the geography of ATIs must be considered in order to obtain the resulting geography of soil changes.

Method and Classification

The complexity and the heterogeneity of the world's soil cover, coupled with those of the rates, areas, and directions of anthropotechnogenic impacts, make it impossible to distinguish any consistent soil change at a global scale. There is, rather, a multitude of soil changes across the face of the earth. What is needed is a global-scale classification of: (1) natural geosystems and soil systems experiencing ATIs; (2) major ATIs as factors in soil change; and (3) historical sequences of ATIs within the general chronology of human impact on soils. The next step would be to establish a matrix of these three classifications as a means of systematizing knowledge for spatial and temporal analysis.

As examples, the following combinations of the three-part matrix might be considered:

1. geosystems in which neither structure nor function has been changed substantially by ATIs, the system existing and evolving primarily in its "natural" course.
2. geosystems in which the biotic and all underground layers are preserved in the natural state, but the surface layers, as atmosphere and hydrosphere, are changed or are changing in concentrations of gases or solutions, that is, slight contamination. Usually these changes occur due to brief, relatively simple, and weak or slight ATIs. The functioning of the systems is affected, but without alteration to the structure of the geosystems, including their biota and soils.
3. geosystems in which the above-ground biotic layer has been altered by strong direct or weaker indirect ATIs, such as forest cutting, pastoral use, or chemical change in atmospheric or hydrospheric components, but in which the major underground layers (the soil and the crust of weathering) have been altered only slightly, if at all. Several cases should be distinguished here. The biotic changes may be such that they do not exceed the "thresholds of sensitivity" of the soil and the crust of weathering and do not affect the basic soil-forming processes. For instance, changes may occur in the composition of a forest or a grass-stand without major impacts on biological turnover or the plant-roots layer. In these cases, soils do not reflect the biotic changes and are sustainable on account of a low sensitivity and/or an ability to process a new environmental signal to support the existing structure. In another set of circumstances, the biotic changes are substantial, but are transmitted into the underground layers only gradually and after substantial delay of varying duration. In such cases, a new, naturallike evolution of soils (and probably of crusts of weathering) begins, proceeding in accordance with physical laws under the influence of changes in the above-ground tiers of a system. The lengthier the duration of the impact, the more and deeper are the changes in the most conservative underground tiers of a geosystem – the soil and the weathering interface.
4. geosystems in which the deeper layers also experience direct ATIs. Here distinctions must be drawn regarding the strength, nature, depth, and rate of the impacts.

Various types of erosional-denudational ATIs, operating through different naturelike mechanisms (aeolic, fluvic, cryosolifluctional, landsliding) are of particular importance within the last type of geosystem. Whereas in some classes of ATIs, certain transformations occur in the underground tier with preservation of the main substance of the tier, soil erosion leads to the partial or complete physical destruction of the structure and substance of the underground tier. The loss of the fine soil is irreversible and irretrievable on the human time scale. For this reason, it is important to assess the losses of fine soil components and the changes in the structure of the soil and crust. Two criteria in assessing erosion must be considered. The first is an estimation of the total amount of fine soils already lost and being lost annually in relation to its total reserve in a geosystem. Special attention needs to be given to the proportions of elements potentially useful for biota, and nonuseful because of such physical and chemical features such as hardness, nonpermeability, salinity, and toxicity. The second is an estimation of the work accomplished by erosion in changing the horizontal structure of the underground tier.

It is possible to construct a sequence of geosystems changed by erosion of underground tiers on the basis of the second criterion, depending on the horizon that has been lost or brought to the surface into contract with biotic and other aboveground tiers. Erosion may proceed within the bio-accumulative horizons, and middle or lower parts of the same have been brought to the surface; eluvial horizons are at the surface; subsoil middle or lower horizons are at the surface (clay-illuvial, alfehumus-illuvial, metamorphic, saline, alkaline, compacted, and so on); the whole soil is removed and various horizons of the crust of weathering or different layers of the underlying loose or hard rocks are at the surface. In all of these cases, which are usually designated as ones of slightly to strongly eroded soils, substantially new natural-anthropogenic bodies or underground tiers of geosystems appear whose properties are determined by combinations of the inherited horizon or horizons of the original soil or crust of weathering with young, usually weakly advanced soil formation or weathering. Depending on the horizon of the natural underground tier on which this new process develops, it may diverge to different degrees from the "pure" model of soil formation and weathering on the original parent rock. A complicated mosaic of soil cover occurs in these conditions, even in stable environments, generated by varying depths and rates of anthropotechnogenic erosion processes.

In order to forecast the consequences of ATIs, it is important to assess the total stock and the stratigraphy of the fine soil in the underground tier of geosystems. A number of classes may be distinguished:

1. shallow (up to 1 m), stony, fine soil thicknesses, underlain by rocks. These are either young Holocenic soils, duricrusts, or very old and strongly eroded soils. Exposed to human activity, they may disappear quickly from the surface, leaving behind rock outcrops in any climate within the human time scale. This ecological catastrophe occurs because the rate of weathering at these surfaces is so low that natural soil formation is extremely slow. The regime of exogenic processes often changes radically at these surfaces after the elimination of fine soil cover. Instead of producing fine materials, these surfaces generate stony material that moves rapidly along the slope. The reproduction of soil on such rocky surfaces is possible only if the fine soil is "imported" from elsewhere and deposited in conjunction with slope terracing.
2. thick (up to 5–10 m) cover of loose and homogeneous sediments with well-developed soils. Loesses and deep sands are the examples of this kind. In this case, even complete soil erosion does not lead to catastrophe, although the loss of soil humus, structure, and stock of nutrients is serious. Even if the friable underlying layers are exposed, however, soil rehabilitation is possible in principle, even within centuries or decades while cultivating. Agricultural management can increase sharply the rate of rehabilitation of productive soil cover on such materials.
3. thicknesses of friable sedimentary rocks, fully developed profiles of soil and crusts of weathering, which are sharply stratified into different layers and horizons, varying in their usefulness for the biota. In this case, erosion and denudation may play different positive or negative roles, depending on the circumstances. Examples are cases in which:
   (a) the sedimentary thickness contains a "comforting" upper horizon, within which the soil is developed, underlain by one that is toxic or unfavorable for the biota (e.g., too compact, structureless, gleyic, or saline). Erosion brings to the surface this "discomforting" layer, in which soil formation is possible, but follows a different process and produces much less productive soil.
   (b) the soil profile consists of contrasting horizons, with upper-structured, organic-rich, porous ones over compacted ones of clay-illuvial, gleyic, cemented, weakly permeable, rich in free aluminum or soluble salts, silica-iron-calcaire-gypsum pans. Soil erosion eliminates the upper comforting horizons and brings the discomforting ones to the surface. This creates many problems for their cultivation and requires the application of extensive technology.
   (c) the upper soil horizons are represented by the most-weathered heavy clay, which is impoverished with total and available bases and does not contain a reserve of weatherable minerals, whereas the lower horizons of soil may be rich in mineral resources, including calcium, magnesium potassium, and phosphorus. Erosion exposes these richer and usually more favorable layers. This is sometimes the case in the humid tropics. On the whole, erosion in such cases may improve the potential fertility of the substratum and does not represent an ecological catastrophe, as long as it is contained within the fine soil horizons of the crust and is not permitted to reach deeper rocky layers, initiating gully erosion and leading to the formation of badlands.

These examples provide a general outline of a sequence of geosystem changes by different tiers. In the analysis of general soil change, this sequence should be overlain by those of the types of ATIs, which would be differentiated on the bases of their substance, intensity of impact, duration, and depth of action, as well as by the sequence of types of natural geosystems and the corresponding soil sequence. Then the three-dimensional matrix can be constructed: natural background, character of the impact, character of change. This matrix subsequently should be expanded to include the fourth dimension of historical evolution of ATIs, specifying the duration and sequence of the impacts.

In considering single ATIs or those that are repeated regularly in time without changes in substance, depth, or strength, the distinction between reversible and irreversible changes is a useful one. Reversible changes occur when, following the impact, physical processes are able to return the system to its original state within a time frame acceptable for human activity. Irreversible changes take place when the rehabilitation structure and functioning of the system is at best only partial. Two outcomes are possible in the case of irreversible change. The physical processes may take a different direction, as in desertification after forest destruction in the forest-steppe zone; or the restoration processes may be so slow that rehabilitation is impossible or impractical on a human time scale, although possible in terms of soil-geological time.

In this connection, it is important to know and classify the features of geosystems and soils by the time spans characteristically involved in their formation and rehabilitation, even by so general a division as between the rapidly and slowly formed. It is also important to understand which of the soil features are formed and reproduced in the contemporary natural setting and which are "relict" features inherited from past conditions of soil formation. It is evident that when the latter are destroyed or changed by ATIs, they will disappear forever. If these relict properties are harmful for present-day land use, their disappearance is desirable and manageable, if there are no ecological side-effects. But if they are useful, then their loss is serious because restoration may be impossible. Thus, for the purposes of analysis, all soil properties should be divided into the reproducible and the inherited nonreproducible.

Where soils are affected by multiple ATIs, the history and evolution of human impact requires scrutiny because of the complexities involved. Analysis of this kind first should consider how ATIs have been recorded in soils. Several possible situations exist. ATIs of differing type, strength, depth, and duration may be recorded in the same soil layers, and the changes overlie each other. ATIs may cause the total or partial destruction of the soil profile by erosion, destroying the traces of previous ATIs together with the destroyed horizons, while the new ATIs act upon the newly exposed deeper horizons. Or, ATIs act at the background of the increasing soil thickness, which is induced by different natural or anthropogenic processes as in cases of siltation or alluvial or sand deposition; different by time, ATIs are recorded in different horizons of the growing soil-lithological column.

The second aspect of analysis should address the time sequence of ATIs. More recent ATIs, by their intensity and depth of impact, may surpass earlier ones, erasing their results in the soil body. Or the earlier ATIs may have introduced irreversible changes, such that the later ATIs are unable to erase the impacts of the former, and, indeed, may be predetermined by them to a considerable degree. Cases exist in which soils are exposed to natural processes of rehabilitation, but the legacy of the ATIs steers the direction of development and the pattern of soil formation away from those that would be expected had the ATIs not occurred.

The main difficulty in the use of these methods for the analysis of global soil change lies in the time element, particularly in specifying the changes that have transpired over the history of human civilization (10,000 years), during the era of European colonization, industrial development, and market-oriented agriculture (the past 300 years), or within the demographic explosion, scientific-technical revolution, and postcolonial development of the past half-century. The development of the three-dimensional matrix compared with a cartographic model of land-use history should provide some revealing insights. More accurate assessment of the quantitative characteristics of change will require detailed studies at varying scales in key areas representing a diversified variety of existing geosystems.

Application of the Method

As noted, the proposed comprehensive approach cannot be implemented at a global scale because of the unavailability of the data. At this time, we can attempt to provide only a very general picture of human-induced global soil change as a trial approximation. This picture will necessarily be more qualitative than quantitative in its basis.

There are, of course, well-known examples of the phenomena of soil degradation, including transformation estimates, that have been generated in recent monographs (Brown 1984; Rozanov 1984; Clark and Munn 1986). A large number of familiar examples come to mind: the Dust Bowl of the 1930s in the United States; water erosion in eastern Nigeria, Tanzania, Lesotho, Ethiopia, India, and Nepal; the salinization of irrigated lands in Iran, Iraq, Pakistan, and Egypt; and pasture degradation in the Sahel and Australia. But focusing upon these cases, even using more accurate data and spatial extrapolations, would provide little progress toward the creation of a reliable global picture of the kind sought in this volume. Therefore, we attempt a cursory use of portions of the three-dimensional matrix as described and consider the applicability of this method to several concrete examples. It must be remembered that, to our knowledge, no one has attempted a 300-year global estimation of human-induced soil change.

The global classification of "natural" geosystems can be made, using, for example, the data and method of Rozov and Stroganova (1979) in a somewhat reorganized form. Five great "latitudinal," or radiational, belts are recognized, each with distinctive radiation balances (Table 12-1). Each of these can be further segmented according to coefficients of atmospheric moisture and the character of the topography. Atmospheric moisture coefficient can be taken as that pro-

Table 12-1 *Global radiation belts*

Symbol/Type	Sum of temperatures above 10°C (C°)	Average annual temperature (C°)	Radiation balance (kcal/cm²/yr)
T – tropical	>8,000	>20	>75
ST – subtropical	4,000–8,000	13–20	50–75
SB – subboreal	2,200–4,000	7–13	35–50
B – boreal	1,000–2,200	1–7	22–35
P – polar	<1,000	<0	11–22

posed by Ivanov (1941), which is a ratio between annual precipitation and potential evaporation. Arid (a = coefficient < 0.3), semiarid ($s = 0.3–0.6$), and semihumid and humid ($h > 0.6$) sectors are identified here. Topographically, we recognize the main types of relief as plains and lowlands (p) and mountains and high plateaux (m). The global pattern is illustrated by Fig. 12.1, showing the radiation belts and moisture sectors of the world.

Each spatial unit – in this case, global sectors – can be characterized by a specific combination of principal soil and land-use types (Tables 12-2 and 12-3). Presently, soils can be assessed only by sector, although we are working toward more detailed assessments. Land-uses can be distinguished as follows: rain-fed agricultural lands, including plantations (A); irrigated lands (I); pastures and grazing lands (R); forests and woodlands (F); and other lands (directly used or not), including sands, rock outcrops, badlands, water reservoirs, lands under settlement, and roads (O). The varying global estimates of land-use types (Table 12-2) reflect the uncertain nature of statistical information – a problem to be considered in all global surveys.

Table 12-2 *Global areas of principal types of land uses*

Land-use types	Areal estimates (10⁴ km²) by Rozov and Stroganova (1979)	FAO production yearbook 1969–71	1980
A – agriculture (rain-fed) + I – irrigation	1,442	1,413	1,452
R – pasture and grazing	3,057	3,126	3,116
F – forests	4,060	4,209	4,093
O – other*	4,608	4,325	4,412
Total*	13,239	13,073	13,073

* Does not include ice cover and inland waters.

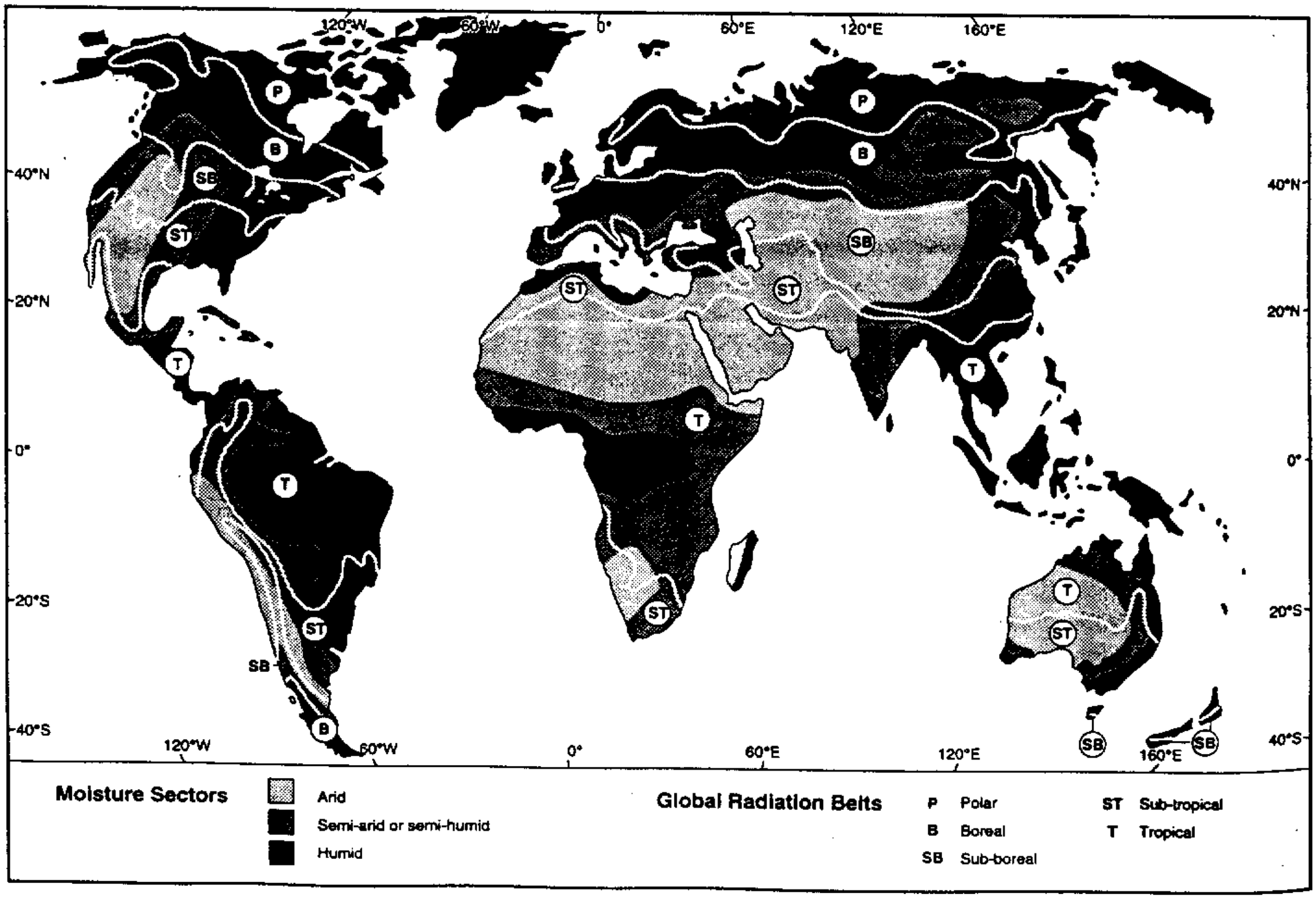

Figure 12.1 Global radiation belts and moisture sectors.

Table 12-3 *Land-uses associated with major environmental/soil regions*

Environmental regions	Dominant soils*	A	I	R	F	O	Total	Present CLU**
		Area of land-uses (10^4 km^2)						
T		360	62	1,407	1,720	2,080	5,269	0.07
Tp		303	62	1,275	1,508	1,761	4,909	0.07
Tm		57	—	132	212	319	720	0.08
Th	ferralsols, nitrosols,	188	—	440	1,330	630	2,588	0.07
Thp	acrisols, plinthosols	161	—	408	1,160	500	2,229	0.07
Thm		27	—	32	170	130	359	0.08
Ts	vertisols, oxic	162	60	570	390	560	1,742	0.13
Tsp	cambisols, ferric	132	60	480	348	440	1,460	0.13
Tsm	lixisols	30	—	90	42	120	282	0.11
Ta	regosols, arenosols	10	2	397	—	890	1,299	0.01
Tap	leptosols, calcisols	10	2	387	—	821	1,220	0.01
Tam		—	—	10	—	69	79	0.00
ST		320	110	620	570	960	2,580	0.17
STp		216	110	413	326	758	1,823	0.19
STm		104	—	207	244	202	757	0.14
STh	nitosols, lixisols,	130	—	50	340	140	660	0.20
SThp	acrisols, alisols	102	—	40	170	58	370	0.27
SThm		28	—	10	170	82	290	0.11
STs	chromic cambisols,	160	60	270	210	160	860	0.22
STsp	calcaric cambisols,	98	60	150	148	100	556	0.23
STsm	vertisols	62	—	120	62	60	304	0.19
STa	calcisols, arenosols,	30	50	300	20	660	1,060	0.07
STap	regosols	16	50	223	8	600	897	0.07
STam		14	—	77	12	70	163	0.08
SB		412	48	570	300	850	2,180	0.21
SBp		351	48	386	138	530	1,453	0.26
SBm		61	—	184	162	320	727	0.08
SBh	cambisols, luvisols	200	—	60	260	80	600	0.30
SBhp		145	—	37	120	60	362	0.40
SBhm		55	—	23	140	20	238	0.23
SBs	chernozems,	212	38	250	40	250	790	0.31
SBsp	kastanozems, solonetz	206	38	186	18	180	628	0.38
SBsm		6	—	64	22	70	162	0.04
SBa	calcisols, regosols,	—	10	260	—	520	790	0.01
SBap	arenosols, solonchaks	—	10	163	—	290	463	0.02
SBam		—	—	97	—	230	327	0.00
B		130	—	190	1,440	620	2,380	0.05
Bp		123	—	153	979	308	1,563	0.09
Bm		7	—	37	461	312	817	0.01
Bh	podzoluvisols, podzols,	130	—	140	870	400	1,540	0.08
Bhp	histosols	123	—	108	719	215	1,165	0.10
Bhm		7	—	32	151	185	375	0.02
Bs	gelic, cambisols	—	—	50	570	220	840	0.00
Bsp		—	—	45	260	93	398	0.00
Bsm		—	—	5	310	127	442	0.00
P	gelic gleysols, histosols,	—	—	270	30	270	570	0.00
Pp	leptosols	—	—	235	30	201	466	0.00

Table 12-3 (*cont.*)

Environmental regions	Dominant soils*	A	I	Area of land-uses (10^4 km^2) R	F	O	Total	Present CLU**
Pm		—	—	35	—	69	104	0.00
Ice cover		—	—	—	—	1,390	1,390	0.00
Inland water surface		—	—	—	—	200	200	0.00
Total land		1,222	220	3,057	4,060	6,270	14,829	0.10

* FAO soil classification.
** Coefficient of land utilization = ratio between arable land and the total area.
Note: For explanation of codes for environmental regions and land-use types see p. 208.

The combination of these criteria provides the first facet of the three-dimensional matrix (Table 12-3). To obtain the next facet of the matrix, it is necessary to classify ATIs. For a first approximation, the main soil-degradation processes associated with different ATIs are used; subsequently, it should be possible to classify ATIs themselves. The principal soil-degradation processes we consider are wind erosion or deflation; water erosion; soil salinization and alkalinization; waterlogging; physical degradation, including compacting, surface crusting, and siltation; destruction, including excavation and the creation of pavements; and chemical contamination. It is also necessary to take into account the degree of soil degradation, which can be estimated for each process by using common an index from soil science: slight, moderate, and strong. Each grade of the index, of course, has a distinct quantitative range for each of the processes.

Finally, the third facet of the matrix involves the history of ATIs. At this time, we distinguish three time scales connected with the major phases of the development of ATIs in the history of human civilization: the past 10,000 years; the past 300 years; and the past 50 years. The impacts of ATIs on the global soil cover, while not yet calculable with any certainty, can be suggested by the following examples.

Losses Due to Irrigation

Estimates are available for the development of irrigated agriculture (Table 12-4). In 1984, out of 2,200,000 km^2 of irrigated land, 1,550,000–1,600,000 km^2 were in the developing countries (mainly in Asia), about 200,000 km^2 were in the USSR, and nearly 250,000 km^2 in the United States. Approximately 50% of the total irrigated land is affected to varying degrees of secondary salinization. Up to 10,000 km^2 of irrigated land are lost annually because of salinization – a loss that is balanced by the reclamation of new lands. This process of loss and compensation has continued throughout the history of irrigation. The losses have not been exactly proportional to the reclamation of new lands, but have increased progressively with the reclamation of lands of lower quality, as in the movement of irrigated agriculture from alluvial floodplains onto higher river terraces.

Table 12-4 *The growth of global irrigated agriculture*

Date (A.D.)	Area (10^3 km^2)
1800	80
1900	480
1949	920
1959	1,490
1980	2,000
1981	2,130
1984	2,200

Sources: FAO 1984; Szabolcs 1984.

From 1700 to 1984, the global area of irrigated land increased from 50,000 to 2,200,000 km^2, while at the same time, some 500,000 km^2 were abandoned as a result of secondary salinization. It follows that within the past 300 years, nearly 2,650,000 km^2 have been brought into irrigated agriculture, out of which about 1,600,000 were affected by secondary salinization, including 500,000 affected catastrophically up to the point of destruction. To these soil losses should be added others induced by waterlogging and salinization of nonirrigated lands along the canals and reservoirs; desertification in the lower reaches of rivers caused by water uptake for irrigation in the middle and upper reaches and by saline drainage into the river (e.g., the deltas of the Amudarja, Syrdarja, Colorado, Ganges, and Indus rivers); and inundation, waterlogging, and salinization of land in places of discharge or storage of saline waters (e.g., Sarykamysh Lake). These losses add 500,000 km^2 to the total.

Therefore, we estimate the total soil loss within the past three centuries due to irrigation to be 1,000,000 km^2 of land destroyed, plus 1,100,000 km^2 of land with diminished productivity due to salinization. These losses are concentrated in sectors Tsp, STsp, STap, and SBsp, in which the main irrigated lands of the world are located and which comprise an area about the size of South Australia or Mauritania. We must emphasize, however, the possible error in the data from which these estimates are derived, even for a technology as important as irrigation.

Losses Due to Desertification

The present state of the vulnerable soil cover in the arid regions of the world is a source of serious concern due to the global progress of desertification. We have, unfortunately, no

Table 12-5 Environmental regions and land uses affected by soil-degradation processes of desertification on arid plains of the world

		Percentage of total area affected by soil-degradation processes									
		Wind erosion			Water erosion			Salinization and alkalinization			
Environmental regions	Land uses	Sl	M	St	Sl	M	St	Sl	M	St	Total (%)
Tsp	A	10	5	5	10	10	25	—	—	—	65
	I	—	—	—	10	—	—	15	10	5	40
	R	30	10	10	20	15	15	—	—	—	100
Tap	A	40	30	20	10	—	—	—	—	—	100
	I	—	—	—	10	—	—	30	20	20	80
	R	20	30	50	—	—	—	—	—	—	100
STsp	A	15	10	5	15	10	5	—	—	—	60
	I	—	—	—	20	—	—	20	10	10	60
	R	30	15	5	20	15	5	—	—	—	90
STap	A	20	15	10	—	—	5	—	—	—	50
	I	—	—	—	20	—	—	20	10	10	60
	R	55	30	10	—	—	5	—	—	—	100
SBsp	A	15	10	5	15	10	5	—	—	—	60
	I	—	—	—	10	—	—	20	15	5	50
	R	30	20	10	15	10	5	—	—	—	90
SBap	A	20	15	10	—	—	5	—	—	—	50
	I	—	—	—	20	—	—	20	10	10	60
	R	55	30	10	—	—	5	—	—	—	100
Bsp	A	—	—	—	—	—	—	—	—	—	—
	I	—	—	—	—	—	—	—	—	—	—
	R	—	—	—	5	—	—	—	—	—	5

Source: Rozanov 1986.
Note: For explanation of codes for environmental regions see p. 208. Other codes: Sl = slight; M = moderate; St = strong.

reliable data on the state of land resources in the arid regions of any country. Our estimates of the areas affected in some way are derived from figures drawn from analysis of numerous publications (e.g., Dregne 1983; Kovda 1977; Mabbutt 1985; Rapp 1987; Stiles 1987) and spatially extrapolated (Table 12-5). We suggest a +/− 25% error factor for these estimates, but they constitute the best obtainable until land survey results from space-based technology can be acquired and interpreted. Damage by various degrees is estimated to have taken place on 570,000–950,000 km^2 of the earth's land surface.

Losses and Degradation in Areas of Rain-fed Agriculture

For this category, it is possible only to provide a qualitative global picture. It is well known that the main regions of expansion of world agriculture in the past 300 years include the chernozemic steppes, plains, and prairies of eastern Europe (Russia), western Siberia (the past 100 years), Manchuria, North America, Argentina, Australia, and New Zealand. At present, these are the principal wheat- and maize-producing regions of the world. In addition, arid lands were also reclaimed for natural or improved pastures. The typical process of loss for these regions involves the conversion of arable land into the category of "other lands," whether settlement features or badlands, and the cultivation of forest and pasture lands to compensate for the loss. Estimates of the degradation of these soils are available from numerous publications, but they are highly inaccurate at a global scale. It is evident that erosion on much of this land is serious, particularly considering its important role in meeting the food needs of the world.

Losses in the Humusphere

The organic substance of soils is humus, and the "humusphere" tends to associated with the upper, humus-rich horizons of the pedosphere. Its content and its composition and the properties of its components react quickly and adequately to an environmental change, whether natural or anthropogenic. Humus is a complex but well-organized system with certain ratios of components conditioned by biothermodynamic causes. The most general regularity of humus is that the higher the thermodynamic and biochemical resistivity of a substance or group of substances, the greater its share in humus composition. At the same time, the ratio of the groups of different resistivity depends on the level of soil biological activity; the content of most labile and easily decomposed compounds is lower in soils with high biological activity, whereas in soils with decreased biological activity, the share of such substances in humus is higher. This first rule of soil humus state can be formulated in another way: the direction of the humification process is conditioned by selection of the most stable substances, under a given thermodynamical environment, and their compounds with mineral components. The second rule states that the depth of humification, or the extent of transformation of organic substances of plant residues into humus acids, depends on the speed of the humification process, which is proportional to the soil biological activity.

These two rules (others follow) allow us to analyze the changes that have occurred in the humusphere within the past several centuries, and are still occurring, as a result of anthropogenic impacts. The system of humus substances is transformed by the change of the conditions of humus substances into an equilibrium with the new conditions. These relations provide a solution to the problem of explaining changes in soil properties observed for a certain time and place, and make it possible to reconstruct and predict the humus state of soils under known tendencies of agricultural or other anthropogenic impact.

In nature, the transformation of humus proceeds rather slowly, save in the tropics, and marked changes require many decades or centuries, save in extreme situations. Anthropogenic impact induces sharp changes of ecological equilibrium, followed by deep and rapid reconstruction of soil organic profiles. The cultivation of "pristine" lands, at least in the majority of cases, historically was accompanied by a considerable decrease of humus content because of increased mineralization and decreased plant residues. Direct observations indicate that the humus stock may be lowered 30–50% in newly cultivated lands within one to two decades. It has been shown at a number of sites that the humus content in cultivated fields was lower by 20–30% on average than in climax forest or meadow soils. At the same time, it would be erroneous to regard this process of mineralization and loss of organic material as permanent. Numerous experimental data show that the content and composition of soil humus can be maintained indefinitely under the proper agricultural management.

This evidence corresponds fully to the general theory of humification: the stability of factors of humification provides for the stability of humus content, stock, and composition. Consequently, the changes in soil properties are conditioned mainly by overall changes in agricultural technology.

The rate of change in humus content and stock varies substantially, depending on the character of the process. The data in this regard are rather contradictory. Under midlatitude conditions, however, only small fractions of a percent may be accumulated within a year. With the formation of a "mature" soil profile, the rate of humus accumulation gradually decreases, and at the climax stage, the processes of new humus formation come into an equilibrium with the processes of mineralization. As a result, the maximum level of humus accumulation for a given set of soil-ecological conditions will be reached in tens and hundreds of years. Substantially different rates are characteristic of "pristine" lands brought under cultivation. In these cases, the rate of humus mineralization will be higher by an order than the rate of humus formation, and, as mentioned, the humus stock may come down by 20–35–50% within a few years. These figures are even larger in the humid tropics.

The human-induced changes in soil organic matter are related not only to the content and stock, but also to the qualitative composition of the matter as well, primarily to its group and fractional composition. These changes are not simple; the same agricultural technology often induces contrary effects depending on the situation in which it is applied.

The group composition of soil humus is conveniently characterized by the ratio of humic and fulvic acid content, the Cha : Cfa ratio. This figure, designating the type of humus or the degree of "humateness," usually increases when human impact on the soil is accompanied by growth of the quantity of organic substances introduced, such as plant residues or organic manures, by growth of soil biological activity, by optimization of soil pH and hydrothermical regime, by provision of soil microorganisms with energy and nutrients, and by growth of seasonal and secular length of the humification process. Hence, the changes in the direction of humification will differ, depending on the ecological conditions of humus formation over comparable time scales.

The second important indicator of humus change is the fractional composition or the distribution of humus substances by their forms of bonds with the mineral components. This indicator changes in time and space more simply than the humus group composition. The ratio of different fractions of humic and fulvic acids in both cultivated and uncultivated soils is a function of pH and the mineralization of soil solution and groundwater. In calcareous and gypsic soils, particularly at higher pH, the humic acids saturated with calcium are dominant. The liming of acid soils and gypsum application to alkali soils will have similar effects. Application of acid mineral fertilizers without prior liming will induce a reverse process of loss of calcium humates and their transformation into free acids or heteropolar-complex salts with iron and aluminum cations. Thus, the extent of a change of humus fractional composition depends directly on the intensity and rates of soil liming, gypsum and mineral fertilizer application, and irrigation with fresh or mineralized water.

For a general assessment of changes in humus fractional composition, it is possible to use the ratio between the second fraction of humus substances (sum of humic and fulvic acids saturated with calcium) and their first fraction (sum of humic and fulvic acids, free or bound with free sesquioxides). This indicator reveals even early changes in humus composition under relatively recent ATIs.

All changes in soil humus within recent centuries are ecologically conditioned; the direction and extent of the changes depend on the concrete conditions and the rates and character of the anthropogenic impact. There cannot be a uniform scheme applicable to all regions and systems of agriculture. In

Table 12-6 *Assumptions for estimates of global changes in the humusphere*

Criteria	Previous to major ATIs	Subsequent to major ATIs: Cultivated soils (15×10^6 km^2)	Subsequent to major ATIs: Anthropogenic badlands (20×10^6 km^2)
Average thickness (humus layer)	0.5 m	0.5 m	0.1 m
Average density (humus layer)	1.3 g/cm^3	1.2 g/cm^3	1.4 g/cm^3
Average organic carbon content	2.0%	1.5%	0.25%
Average stock of organic carbon	13,000 t/km^2	12,000 t/km^2	350 t/km^2
Total stock of organic carbon in humusphere	1,700,000 million t (1.7×10^{18} g)	180,000 million t (1.8×10^{17} g)	7,000 million t (7.0×10^{15} g)

Note 1: See Kovda 1970; Grigorieva 1980.
Note 2: Present total stock of organic carbon in humusphere = 1,432,000 million t (1.4×10^{18} g)
Note 3: Organic carbon lost from humusphere from the Neolithic to present = 268,000 million t (2.68×10^{17} g)
— involving anthropogenic badlands = 253,000 million t (2.53×10^{17} g)
— involving existing cultivated lands = 15,000 million t (0.15×10^{17} g)

order to estimate the loss of organic matter as a result of ATIs on the humusphere, it is necessary to derive calculations on the basis of the world soil map in accordance with the general principles already stated. At present, we can construct only a very approximate global picture founded upon several basic assumptions (Table 12-6).

The calculations show that within the history of agricultural civilization, the following quantities of organic carbon were lost from the humusphere of the planet: from the anthropogenic badlands, 253,000 million t; from the existing cultivated land, 15,000 million t; totaling 268,000 million t. Placing these figures into broad time scales used, the losses are estimated as: within the past 10,000 years, 253,000 million t; within the past 300 years, 90,000 million t; within the past 50 years, 38,000 million t.

Therefore, the total losses of organic carbon from the humusphere of the earth, within the history of agricultural civilization, and the accompanying formation of anthropogenic badlands and of contemporary cultivated lands, comprise 268,000 million t, or 15.8% of its original stock. These estimates, again, should be regarded only as approximations that indicate the general trend of the process.

These figures could be interpreted in terms of rates of "dehumification" during the times under consideration. If within the past 10,000 years, the loss of humus occurred at an average rate of 25.3 million t/yr, then within the past 300 years, it accelerated to 300 million t/yr, and within the past 50 years, it became as high as 760 million t/yr. By any time scale, the process appears to have accelerated logarithmically, and this situation should be regarded as ecologically dangerous.

Concluding Remarks

It is understandable that the analysis that has been given of the present state of the world's soil cover and of its changes under the impact of ATIs in various time scales, particularly the past 300 years, represents only a first approximation. This caution noted, we estimate that human activity has altered the fundamental condition of soils throughout the world, albeit with regional variations. The magnitude and spatial scale of the transformation may rival or exceed those associated with deforestation (chap. 11) and atmospheric pollution. Indeed, we estimate that the amount of lands severely damaged or rendered useless for agriculture exceeds the area that is currently cultivated. Other forms of transformation also have been important and are escalating, such as dehumification.

It is curious that so little research of this kind has been undertaken that a standard method of analysis does not exist. For this reason, it has been necessary to propose such a method here. The analysis and estimates that follow from it obviously can be improved through compilation and use of the appropriate soil maps and statistical data by countries and continents. The global picture that will be drawn in the future should be not only more accurate, but, equally important, should also show more detail by types of natural geographic situation, ATIs, and time scales. This will make it more operation-oriented – useful not only for the prognosis of future global or regional soil changes, but also for the management of these changes.

References

Brown, L. R., ed. 1984. *State of the World. 1984: A Worldwatch Institute Report on Progress Toward a Sustainable Society*. New York: W. W. Norton.

Clark, W. C., and R. E. Munn, eds. 1986. *Sustainable Develpment of the Biosphere*. Cambridge: Cambridge University Press.

Dobrovolsky, G. V., and I. S. Urusevskaja. 1984. *Soil Geography*. Moscow: Moscow University Press. (In Russian.)

Dregne, H. 1983. *Desertification of Arid Lands*. Harwood: Chur.

FAO. 1981. *Production Yearbook, 1980*. Rome: Food and Agriculture Organization, United Nations.

———. 1984. *Production Yearbook, 1983*. Rome: Food and Agriculture Organization, United Nations.

Grigorieva, T. V. 1980. Turnover of the main elements of the biosphere. In *Turnover of Substances in Nature and Its Change by Economic Activity of Man*, ed. A. M. Ryabchikov. Moscow: Moscow University Press. (In Russian.)

Ivanov, B. G. 1941. Moisture zones of the earth. *Izvestia Academii*

Nauk SSSR, ser. Geogr. and geophys. 3: 8–26.

Kovda, V. A. 1970. Soil science and the productivity of the biosphere. *Vestnik Academii Nauk SSSR* 6: 8–13. (In Russian.)

———. 1977. *Aridization of Land and Drought Control*. Moscow: Nauka. (In Russian.)

———. 1981. *Soil Cover: Its Improvement, Use, and Protection*. Moscow: Nauka. (In Russian.)

Mabbutt, J. A. 1985. Desertification of the world's rangelands. *Desertification Control Bulletin*, UNEP, Nairobi, 12: 5–11.

Rapp, A. 1987. Desertification. In *Human Activity and Environmental Process*, ed. K. J. Gregory and D. E. Walling, 425–43. London: John Wiley and Sons.

Rozanov, B. G. 1984. *Bases of the Environmental Science*. Moscow: Moscow University Press. (In Russian.)

———. 1986. Land Resources of the Arid Belt of the USSR, Their Rational Use and Conservation. *Problemy Osvoenia Pustyn* 5: 22–28. (In Russian.)

Rosov, N. N., and M. N. Stroganova. 1979. *Soil Cover of the World*. Moscow: Moscow University Press.

Ryabchikov, A. M. 1972. *Structure and Dynamics of the Geosphere, Its Natural Evolution and Change By Man*. Moscow: Moscow University Press. (In Russian.)

Stiles, D. N. 1987. Camel vs. cattle pastoralism: stopping desert spread. *Desertification Control Bulletin*, UNEP, Nairobi, 14: 15–21.

Szabolcs, I. 1984. *Impact of Irrigation on Soil and Water Salinity: Failure Due to Salinization*. Budapest: Research Institute for Soil Science and Agricultural Chemistry.