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CURRENT PROBLEMS IN RESEARCH

Reappraisal of the Soil

Pedogenesis consists of transactions in matter and energy between the soil and its surroundings.

C. C. Nikiforoff

What is soil? Soil technologists and agronomists define soil as the medium which provides the foothold and the mineral nutrients for land vegetation. Agronomy inherited this old concept of soil from the tillers of land, for whom the soil is just the "dirt" supporting their crops. This simple utilitarian concept of soil is so deeply entrenched in people's minds that one may wonder whether it would not be less confusing to leave the term *soil* entirely to agronomy and coin some other name for the geochemical surface formation which is referred to in agronomy as "the soil."

Without agronomic bias, the soil or its geochemical equivalent might be defined as an excited skin of the subaerial part

of the earth's crust. In order to clarify this definition it is necessary to define *earth's crust* and to say a few words about the nature of the excitation of its integument.

Earth's Crust

The term *earth's crust* is intended to designate the 10-mile-thick outermost layer of the silicate geochemical shell. This shell, the probable thickness of which is in the neighborhood of 100 kilometers, consists of igneous rocks and their derivatives. Igneous rocks are largely made up of oxygen, silicon, and a half-dozen other elements, including aluminum, iron, calcium, potassium, sodium, and magnesium. These eight ele-

ments make up more than 98 percent of the mass of igneous rocks. Less than 2 percent of the shell is made up of other elements, the contents of which range from several tenths of one percent (for titanium) to mere traces.

Oxygen makes up only a little less than half of the whole mass of the shell, but, because its density is low, it constitutes by volume more than 90 percent of the bulk. Silicon is the next most abundant element in the earth's crust. It makes up about 27 percent, by weight, of igneous rocks (1). The density of silicon, however, is much higher than that of oxygen; hence, in igneous rocks silicon constitutes less than 1 percent of the volume. Aluminum and iron are the only other elements each of which makes up more than 5 percent of the mass of the earth's crust (1).

On the average, there are about 63 atoms of oxygen in every 100 atoms making up the earth's crust. All the oxygen is combined with other elements to form various oxides, which are arranged into crystalline lattices of rock-forming minerals, such as quartz, feldspars, and pyroxenes.

Crystals of silicates, which make up more than 90 percent of the mass of igneous rocks (1), are essentially oriented clusters of large oxygen ions, thoroughly interbraced by the much smaller ions of silicon and aluminum and holding ions of other elements in the interstices of the

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silicon-oxygen framework (2). Individual atoms in a crystal are arranged in such a way that inside the lattice all valences are fully satisfied, all electronic charges are balanced, and each atom is accommodated according to its space requirement and coordination habit (3). These rules do not apply to the atoms on the surface of crystalline structures, which carry free charges, possess some amount of open valence, and have their coordination number only partly met. The electrostatic charges and open valences of these atoms serve as the root of the surface energy of crystalline structures and provide the braces uniting various crystals into a massive rock.

On the surface of the earth's crust, solid rocks make contact with the atmosphere and become subject to weathering, the general trend of which is toward the ionic dispersion of matter. In the course of this process, somewhere between the initial and final stages, the solid rocks are broken down into loose earthy material. This intermediate product of weathering consists of sand, silt, and clay, with an admixture of coarser fragments of initial rocks.

By far the greater part of this loose material does not remain in place but is shifted and assorted by running water, wind, or glaciers and is redeposited in other places. As a result of these movements the thickness of regolith varies, from place to place, from virtually nothing to several kilometers (4).

This is the loose mantle of the earth's crust, the outermost layer of which, having a thickness of hardly more than 2 or 3 meters, is permanently excited and transformed into soil.

Exogenic Excitation

Excitation of the skin of the earth's crust is caused by the continuous application to it of extraneous energy. Energy flows toward the surface of the earth from two different sources. Part of it is cosmic and flows from the space outside the earth. Another part is generated in a slow atomic decay of radioactive elements inside the crust. For brevity, let us call these types vadose energy and juvenile energy, respectively.

Solar radiation annually intercepted by the earth and representing the bulk of vadose energy amounts to about 1.27×10^{21} kcal (5). About 57 percent of it is reflected from the clouds, absorbed in the atmosphere, or scattered through space (6). The remaining 43 percent, equivalent to about 5.5×10^{20} kcal per year,

passes through the atmosphere and reaches the surface of the earth, by which it is absorbed and where it is transformed into heat and chemical energy. The surface of the earth has an area of about 5.1×10^{18} cm². Hence, on the average, the rate of inflow of vadose energy amounts to about 108 kcal/cm² per year.

Annual rainfall on the land amounts to about 1.23×10^{14} metric tons, or roughly 120,000 km³ of water. About 78 percent, or some 96,000 km³, of this water is provided by evaporation from the land (7). Evaporation of this water requires about 5.8×10^{19} kcal, or some 36 percent of the solar radiation received by the land. Thus, on the average, more than one-third of the incoming energy is consumed in the evaporation of water, leaving about 68 kcal/cm² per year to warm up the absorbing body.

Raising the temperature renders the receiving body radiant; hence, the earth's surface sends back into the atmosphere a part of its energy in the form of infrared radiation, which is largely absorbed in the air and warms up the lower layer of the troposphere. Another part of this heat generated on the surface of the land is transferred into the ground. Such an inflow of vadose energy, however, does not penetrate the ground very deeply. At a distance of only a few meters from the surface it meets the counterflow of outgoing juvenile energy.

The average thermoconductivity of the earth's crust is 0.004 calories (8), and the average geothermal gradient is about 30°C per kilometer. Under these conditions the flow of juvenile heat is very slow indeed. The pressure of this current of energy, however, is great, as is shown by its ability to check the many-times-faster inflow of the vadose energy at such a short distance from the point of entrance of this energy.

Thus, the skin of the subaerial part of the earth's crust, having a thickness of only a few meters, might be conceived of as a sort of thermal pool into which flow two streams of energy. The capacity of this pool is determined by the temperature above which the excess of energy is discharged into space. The inflow of juvenile heat contributes very little of its own energy to the pool, but it buffers dissipation of the vadose heat into the ground and serves to keep a fairly high energy level in the pool. This is the extraneous energy which excites the skin of the earth's crust. The rate of inflow of this energy varies from place to place and determines the degree of excitation of the receiving system at any given point.

Soil Dynamics

Continuous charging with extraneous energy transforms the thin exterior layer of the relatively inert crust of the earth into a thermodynamic system. The performances of this system, referred to collectively as soil dynamics, represent the totality of movements which continuously are made throughout the system. Some movements are very slow, whereas others are made in a flash. Some movements consist of mere oscillation of an atom in the crystalline lattice; others result in transporting millions of tons of dissolved substances from the continents into the oceans (1), so that some movements cover just a fraction of 1 angstrom while others extend for many kilometers.

Every movement, whether large or small, is a change in place or position and represents a certain amount of work, which consumes an equivalent quantity of energy. The amount of work which might be performed by the system depends upon the free energy of this system. If the intrinsic energy of the system is exhausted and the system is not recharged, then its activity comes to a standstill. Ceaseless excitation of the soil system by vadose energy enables it to function throughout geological history.

An essential part of soil dynamics consists of movements in the atomic and subatomic regions—that is, movements representing various chemical reactions. An ordinary chemical reaction is caused by the collision of sufficiently excited molecules or ions (9). Excited ions of the solid phase of the soil system, however, are mounted in a crystalline lattice on the surface of solid particles. They may rotate or oscillate but cannot move from their nests unless kicked out by other ions. Hence, collisions take place when free ions, disseminated in the liquid and gaseous phases of the soil system, bump into the mounted ions.

Reactions between the solid and non-solid phases of the system show that this part of soil dynamics consists largely of acts of surface chemistry and bring out the significance of the comminution of soil solids. The rate of a chemical reaction is, of course, proportional to the active mass of the reactants. The active mass of soil solids consists essentially of the excited ions which form the mono-ionic surface film of solid particles and, thus, is proportional to the specific surface of this material or inversely proportional to the particle size. The active mass of dispersed 1-micron clay presumably is more than 100 times greater than that of fine sand.

Oxidation, Carbonation, Hydration

The surface of soil-solid particles is bombarded especially by the free ions of oxygen, carbon dioxide, hydrogen, and hydroxyl of dissociated water as well as by the whole, bipolar water molecules. When water vapor condenses to rain water, some quantities of free oxygen, carbon dioxide, ammonia, and other gases are dissolved in this water.

The rain water which falls on land brings with it about a billion tons of dissolved free oxygen and almost an equal amount of dissolved carbon dioxide (10). Like all natural waters, it contains also some free hydrogen and some hydroxyl ions.

A certain part of this water is intercepted by vegetation or evaporates from the surface without entering the ground. The remaining part percolates slowly through the porous ground and comes into intimate contact with mineral particles; this allows dissolved free ions to react with the ions on the surfaces of these particles.

Steady inflow of free ions of oxygen, carbon dioxide, hydrogen, and hydroxyl, as well as inflow of polar water molecules, results in the conspicuous oxidation, hydration, and carbonation of the excited skin of the earth's crust. Indeed, various other ions, including those of calcium, potassium, iron, and sulfur, some of which might be washed by rain from the air but which are largely kicked out by hydrogen ions from broken crystalline lattices, also appear in solution and take part in reactions, thus inflicting other changes in the composition and structure of the system.

Oxidation results in fixation of free oxygen. Since dry oxygen is more or less inert, the free oxygen dissolved in rain water is the principal agent. Oxidation is essentially a surface phenomenon, and free oxygen brought into the system is consumed largely near the surface. The chief recipients of it are ferrous iron, which is oxidized to ferric compounds, and organic carbon, which is oxidized to carbon dioxides.

Carbonation, or enrichment of the system in carbon, is manifested in two different forms—an enrichment in organic carbon, about which more will be said later in this article, and enrichment in carbonates of "mineral" carbon. Carbonates of alkalis and alkaline earths are among the commonest products of chemical weathering. They remain in the system, however, only under certain conditions, which are not universal. When there is an excess of CO_2 they change to

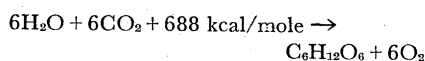
easily soluble bicarbonates, pass into solution, and, if there is sufficient rainfall, may be quantitatively leached from the system to be carried to the sea or into the deeper parts of the earth's crust.

Hydration leads to the general enrichment of the system in water and to formation of hydrates and hydrated secondary minerals such as various clay minerals. Hydrolysis is another conspicuous process in the decomposition of silicates. The role of water in soil dynamics, however, is not restricted to hydration and hydrolysis. Water acts in so many different ways that its role cannot be adequately described in a short article.

Exergonic and Endergonic Processes

Oxidation and hydration as well as formation of carbonates and other salts, like all spontaneous natural processes, are essentially exergonic. Some part of the free energy is consumed in all these processes, whereas the entropy of the system increases. Should operation of the system consist wholly of exergonic processes, the intrinsic energy of the system would sooner or later be exhausted, and further operation would become impossible. Soil systems, however, have been active throughout geological history. We know of no traces of the beginning of this activity, nor can we find any symptom of its probable end. Hence, exergonic processes in the soil must be balanced by the reverse endergonic processes which replenish the free energy of the system. In fact, the rate of inflow of fresh energy through endergonic activity determines the possible amount of exergonic performance of the system. So little is known, however, about the thermodynamic properties of the silicates and other rock-forming minerals that the energy balance of soil dynamics cannot be analyzed at the present time.

The best known endergonic process is the enrichment of soil in organic carbon. An essential part of this process—photosynthesis—takes place outside the soil. It is the function of green plants. Photosynthesis by land vegetation consumes about 60 to 70 billion metric tons of CO_2 per year (11). The over-all formula (12) for this process is:



Thus, photosynthesis on land results in fixation of about 18 billion metric tons of carbon and about 1.7×10^{17} kcal of solar energy per year. On the average it amounts to fixation of about 3.4 milli-

grams of carbon and about 33 calories per square centimeter, per year. Eventually the organic material holding this carbon and energy is turned over to the soil, where carbon undergoes oxidation back to CO_2 and energy is released.

Another endergonic process is the comminution of solids. At present this process can be described only in qualitative terms, because of the lack of information about its scope. As a general rule, breaking of a chemical bond requires application of energy, which is absorbed by the products of the process. The sum of the free energies of disunited ions is greater than the free energy of a molecule which has been made of these ions. The sum of the surface energies of fragments of a crystal is greater than the surface energy of an unbroken crystal. Virtually nothing is known about the rate of energizing soils by this process.

Steady State of Soil System

Under the obvious influence of the philosophy of biological sciences, soil scientists have conceived of the soil as an "independent" natural body, and this body—very vaguely, if at all, defined—has been endowed with certain attributes peculiar to organisms (13). One such attribute is the faculty of growth and of aging from youth to maturity to ultimate senility. Some rather allegoric statements of the pioneers of soil science, such as Dokuchaev's dictum that "soil, like any other plant or animal organism, eternally lives and changes, now progressively and then regressively" (14), have been taken literally and have been uncritically elaborated into the untenable theory of metaphysical soil "ages."

Every thermodynamic system tends toward equilibrium with its surroundings, and such a condition might be approached very closely if the surroundings remain constant long enough. This tendency toward equilibrium is an inevitable consequence of the law of mass action. The term *equilibrium* may be somewhat confusing because of insufficient appreciation of the difference between dynamic and static equilibria. Dynamic equilibrium is the state at which the forward and the reverse processes do not cancel one another but operate simultaneously at equal rates (15). In such a state a new molecule is formed at some point of the system for every similar molecule annihilated at the same time at some other point, so the concentration of these molecules or substances in the system does not change in spite of continu-

ous creation and destruction of these particular molecules or substances. The best illustration of dynamic equilibrium is the reversible process or a cyclic series of consecutive reactions. Both of these are possible only under the conditions that exist when extraneous energy is steadily applied to the system.

Physical and chemical processes in soils collectively represent what we call the "pedogenic process." This process itself is not cyclic. The dynamic equilibrium, or a steady state of the soil system, is maintained by the broader geochemical cycles, in which the pedogenic process makes up only a short segment. Thus, the pedogenic process might be likened to the section of an aggraded stream between two bends. Continuously some water is discharged beyond the downstream bend, and simultaneously the same amount of water flows from beyond the upstream bend. Nothing is lost or gained between the bends, but water runs steadily and performs some steady work. Time and time again we may come to the bank to observe the same pattern of ripples or hear the same warbling of a rapid, although the water is never the same. The steady state of a stream between two bends is maintained by a galaxy of factors, including steady evaporation of water by solar energy, distribution of water vapor by winds, condensation of this vapor, and a steady rainfall over the headwater region. All this takes place outside the channel and the area traversed by the stream, but all these factors collectively serve to maintain a steady performance of the stream. Naturally, the steadiness of stream activity lasts only as long as the base of erosion, the gradient of the stream, the sources of water, and other conditions remain constant.

The corresponding "stream" in the pedogenic process is the stream of ions of various elements and energy. The migration of carbon atoms is understood somewhat better and in greater detail than the movement of other elements. Hence, a brief review of the behavior of carbon in the pedogenic process might illustrate the point.

Migration of Carbon

An enrichment of the initial material in carbon is a conspicuous feature of soil formation. The average content of carbon in igneous rocks is about 0.1 percent (1), whereas the content of organic carbon alone in some grassland soils is well above 5 percent (16). Usually this en-

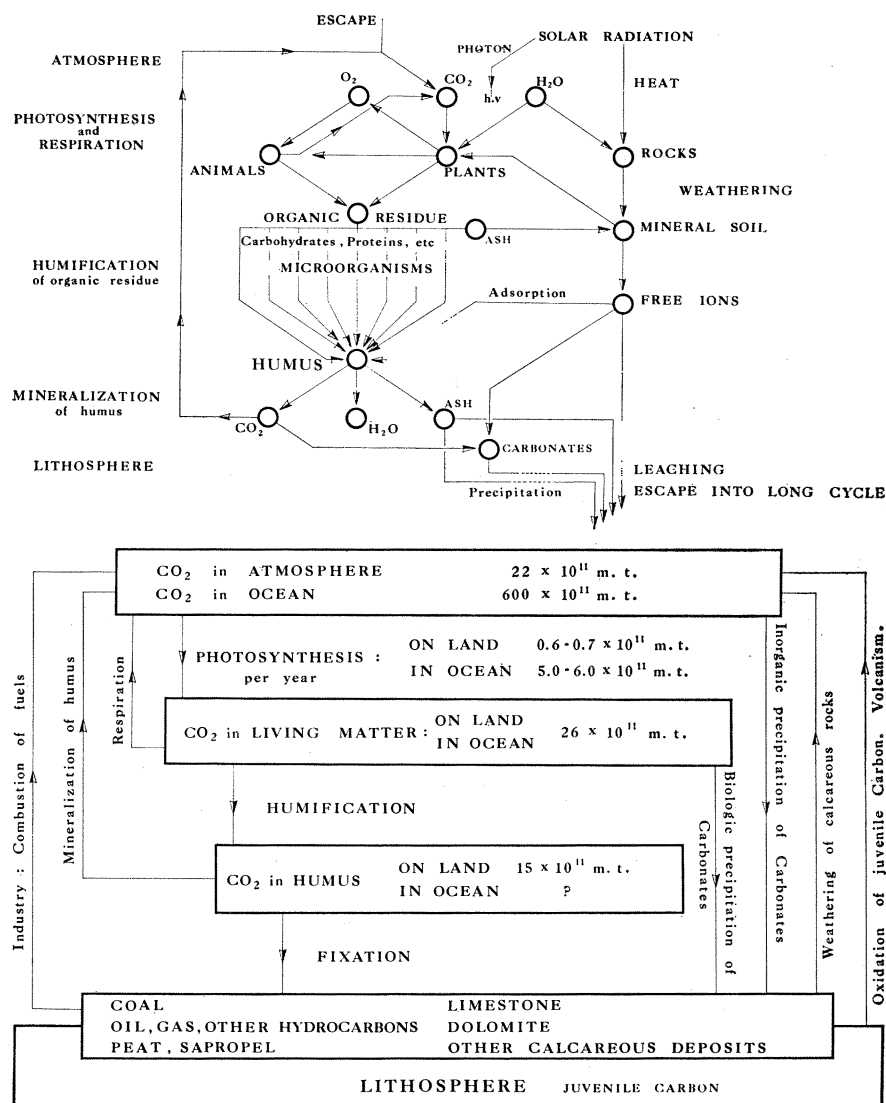
richment is referred to as accumulation of organic carbon. The term *accumulation* is rather misleading. Actual accumulation takes place only at the beginning of the process; the rate of accumulation gradually dwindles to the vanishing point as the system approaches equilibrium. Thereafter the content of carbon remains constant as long as the steady state is not disturbed.

It has been pointed out already that photosynthesis by land vegetation fixes, on the average, about 3.4 milligrams of carbon per square centimeter per year. Life on earth changes its morphological aspect, but its volume, presumably, is a geochemical constant (17), determined by such factors as the concentration of CO_2 in the atmosphere and the ocean, the intensity and distribution of solar radiation, the rate of release of essential elements by chemical weathering, and

the availability of water. Thus, carbon does not accumulate in living matter. Assimilation of free carbon by photosynthesis is more or less balanced by oxidation of organic carbon.

The detailed balance sheet for carbon cannot be discussed here. Nor can we discuss any movements of carbon atoms other than pedogenic. For our purposes it is enough to point out that an amount of carbon, equal to the mass of carbon assimilated by photosynthesis less the amount of this element released by respiration of organisms [about 15 percent of the value for photosynthesis (11)], is turned over to the soil in the residue of dead organisms. In the soil this residue undergoes mineralization or gradually breaks down into the simplest end products, such as water, carbon dioxide, ammonia, and some simple salts.

Fresh organic residue consists of dif-



Geochemical cycles of carbon. (Top) Short cycles; (bottom) long cycles. Estimates of the amounts of CO_2 in long cycles are based on data suggested by Vernadskiy (see 17), Clarke, Fersman, Noddack, Wickman, Goldschmidt, Mason, and others. Their purpose is merely to give some idea about the probable order of magnitude.



(Left) Profile of a podzol, a forest soil of the humid temperate belt. The light band near the surface of the soil is the bleached "eluvial" horizon, in which all relatively unstable primary minerals, including feldspars and ferromagnesian minerals, undergo drastic decomposition. Virtually all products of decomposition are washed out by rain water, so the bulk of this horizon consists of finely crushed crystals of quartz. The outermost part of the horizon is marked by dark soil humus; beneath the bleached zone is the dark "illuvial" horizon in which the products of decay of primary minerals may be partly recombined into the secondary clay minerals. (Right) Profile of a chernozem, a typical grassland soil. The dark upper horizon of this soil is the zone of enrichment in organic carbon. Beneath it is the zone of local concentration of free carbonates, largely CaCO_3 . Concentration of carbon in the upper horizon, the thickness of this horizon, the depth at which free carbonates begin to precipitate, and the content of "mineral" carbon in the second horizon are among the principal chemical and physical coefficients which, collectively, define the equilibrium constant of this soil, adjusted to its physical and biological environment.

ferent substances: carbohydrates such as cellulose and lignin, proteins, fats, resins, waxes, and so on (18). Some substances decompose readily and in a short time. Some others are more stable and persist for several years. Still others survive for many years. Decomposition of organic residue is the work of soil microorganisms which scavenge organic residue but build their own bodies. They break down the protein of old residue, including their own dead, and synthesize new protein in their bodies. Thus, mineralization of the yearly installment of fresh residue takes more than a year—under certain conditions, even many years—and each year a new installment is added to what has been left from the preceding years. Theoretically, at the beginning of the process some accumulation of organic matter, and hence some increase in the concentration of carbon in the soil, must take place. The number of carbon atoms undergoing oxidation, however, must increase with the increase in concentration of these atoms in the system, so that sooner or later a condition is reached in which the number of carbon atoms being oxidized or otherwise inactivated equals the number of new active atoms of this element being added to the system at the same time. When such a condition is reached, the system reaches a steady state and remains thereafter in this state as long as its surroundings do not change. An essential characteristic of this state is that the composition of the system does not change, whereas its mobile compounds are subject to steady replace-

ment, atom for atom or molecule for molecule.

Oxidation of organic carbon does not compensate for the assimilation of carbon by photosynthesis. A certain part of organic carbon escapes oxidation, being deflected into the channels of long geochemical cycles in the course of which various carboniferous deposits (peat, coal, petroleum, and so on) are formed. The discussion of these cycles is beyond the scope of this article.

Enrichment of the soil in organic carbon does not cover other movements of carbon atoms. Photosynthesis is not the only means of entry of carbon into the soil. It has been pointed out already that a fairly large amount of dissolved CO_2 is brought to the soil by rain water. Another undetermined but undoubtedly large quantity of carbon is released by the solution of limestones and other calcareous rocks. Again, not all carbon dioxide produced by oxidation of organic carbon escapes into the air. A certain part of it is dissolved in the soil water.

The dissolved CO_2 —more correctly, free ions of carbonic acids (CO_3^{--} and HCO_3^-)—reacts with free bases, especially the hydroxides of alkalis and alkaline earths, to form carbonates.

As mentioned earlier, at the point where there is an excess of CO_2 , the carbonates change into the more soluble bicarbonates and may be leached out. Hence, carbonates remain in the system only if their rate of solution is lower than their rate of formation. These rates refer to the number of molecules that are

broken down and the number of similar molecules that are formed anew in a given time. Here, again, at the beginning of the process an accumulation of carbonates takes place; but the rate of such an accumulation decreases exponentially until the steady state is reached, at which time the content of carbonates becomes stabilized, due to the compensation for solution and leaching provided by the formation of new molecules.

The concentration of the mobile compound in the system which has reached a steady state depends upon the ratio between the rates of formation and annihilation of this particular substance. The wider this ratio, the higher the concentration of the compound in question.

The ratio between the rates of formation and annihilation, or the rate of capture of free ions by the system and the rate of escape of similar ions from the system, may or may not be uniform throughout the system. The rate of annihilation or escape may be high enough to prevent any accumulation in one part of the system but may drop below the rate of formation to make accumulation possible in another part. Thus, not only the presence or absence but also the concentration of mobile compounds and their distribution throughout the system depend upon the basic ratios between their rates of formation and destruction.

According to the old concepts, which still have a wide circulation, the soils are subject to aging, and therefore concentrations of mobile compounds in the system either increase or decrease with

passing time and the specific parts of the system harboring these compounds either expand or shrink. These somewhat naive ideas are merely a sort of persistent resonance of the philosophy of biological sciences which influenced the pioneers in soil science.

Soil Profile

The migration of carbon is sketched here merely as an example of the general trend of the migration of elements through the soil. Atoms of oxygen, nitrogen, calcium, magnesium, potassium, sodium, iron, sulfur, phosphorus, manganese, and other elements pass in endless procession along similar courses. Some of them come from the air or the ocean; others are released by weathering from the primary minerals. Ions which escape from the soil may disseminate through space, be carried to the ocean, or sink into the zone of anamorphism. Soil science is not concerned with where they come from or where they go after leaving the pedogenic part of the cycle. The destiny of these atoms outside the soil is beyond the scope of this discipline, which is oriented toward counting these atoms and watching their performance on one particular and short stretch of their route.

The soil serves as a sort of turnstile through which pass endless swarms of atoms of excited matter. Most of these atoms participate in a series of consecutive reactions en route. Individual reactions are more or less localized; some of them take place near the surface, others at one or another depth. Thus, organic carbon is oxidized predominantly in the outermost part of the soil, whereas free carbonates precipitate largely (though not exclusively) at some depth.

Each reaction imparts to the initial material certain new characteristics. To begin with, the products of various reactions are concentrated in different parts of the system; hence these parts, enriched in different elements or compounds, acquire individual composition, structure, consistence, and perhaps color.

Not all such alterations of the initial material are caused by chemical reactions. Some of them are effected by mechanical processes, such as shifting and rearrangement of finely subdivided substances by percolating water inside the soil or, on the surface, by runoff, wind, ice, or other agencies.

Every process or reaction is accompanied by a certain change in the energy content of the reactants and of the prod-

ucts. Various reactions require a different activation energy, which serves as a sort of trigger. Some processes are endergonic, whereas others are exergonic. Hence, each individual part of the system is characterized by its own energy requirement and energy balance. In some parts, potential energy is stored; in others, energy is unlocked.

Localization of different forms of activity and the differential alteration of the initial material by these forms of activity render the soil somewhat layered, imparting to it a conspicuous profile. The term *profile* calls to mind a certain curve, and this is exactly what a graphic reconstruction of the soil profile is.

A maximum intensity of any property of the soil is at some particular level of the system. Away from this level, the intensity of this property dwindles to the vanishing point. Now, if the soil is cut into slices, if the value of a given property is determined for each slice separately, and if the results are plotted on a diagram against the depth, then we obtain a curve representing the soil profile with respect to this particular property. A combination of curves showing profiles of all essential properties of the soil makes up a graphic reconstruction of the whole soil profile.

A soil profile shows the paragenetic system of individual soil horizons. In a purely formalistic way, a soil horizon is defined as a layer of soil, roughly parallel to the land surface, which differs from the other layers of the same soil in one or several determining characteristics, such as color, composition, and consistence. The essence of genetic soil horizons, however, lies in the functions which they perform rather than in their morphology. Individual soil horizons are the working aggregates of a complex thermodynamic system. With respect to their relationships to the whole system, they might be likened to the organs in a living body, each of which is adapted for the performance of some specific functions. Continuous performance of its specific functions imparts to each horizon its individual chemical and morphological character.

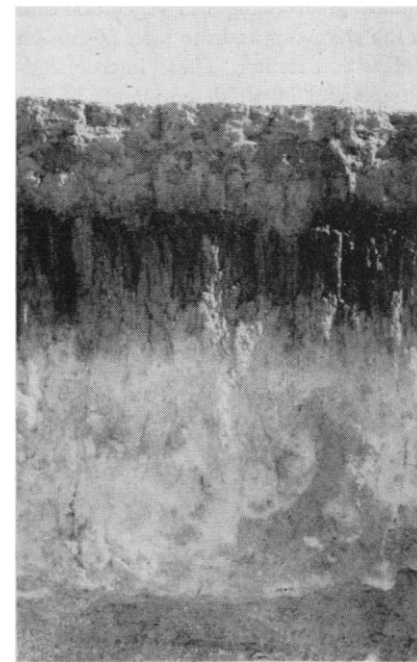
The uppermost soil horizon usually is enriched in organic carbon. One of the essential functions of this horizon is oxidation of organic carbon to CO_2 , a process referred to sometimes as "soil respiration." Oxidation of carbon is accompanied by release of stored vadose energy, which is another conspicuous function of this horizon. Decomposition of organic residue in this horizon is brought about by the soil microorganisms

which produce various enzymes. Enzymes are powerful catalyzers which accelerate chemical decomposition of minerals and release of free ions. Thus, production of enzymes is the third important function of the upper soil horizon. Another horizon might be adapted for a particularly effective hydrolysis of certain aluminosilicates and production of clay minerals. Still another horizon is adapted for precipitation of carbonates. These are just a few examples of specific functions of individual soil horizons.

Legend about Soil Evolution

Every thermodynamic system in equilibrium with the surroundings reacts to changes in the surroundings in such a way as to free itself of stresses caused by these changes (Le Châtelier, 19). The relief of internal stresses is achieved by the shift of equilibrium from one level to another with a corresponding change in equilibrium constant.

The surroundings which determine the steady state of the soil are a local combination of the climate, the land form, the biological pressure, and the initial material. These four determinants are



Profile of the soil of arid regions, showing a conspicuous prismatic (dark) horizon which might indicate "solonization" of the soil. Some physical and chemical properties of such soils render the latter unproductive for plants. Amelioration of these soils is difficult and costly. Usually such soils do not occupy large continuous areas but occur in small spots, scattered throughout the land, occupied by nonsolonized or weakly solonized soil.

recognized as the essential factors of soil formation. Maintenance of the steady state of the soil requires that these factors remain more or less constant. Their constancy is not absolute, indeed. To begin with, the intensity of irradiation of the land is subject to daily and seasonal fluctuations due to the earth's rotation on its axis and revolution about the sun. Hence, vadose energy comes to the soil in daily and annual waves which cause the steady state of the system to oscillate about a certain mean position. In addition to these more or less rhythmic vibrations of the steady state, some erratic deviations from the mean, representing a degree of imperfection of nature, also disturb the steady state. These sporadic deviations are caused by yearly differences in amount and distribution of rainfall, in mean temperature, in cloudiness, and so on. Presumably, these relatively small disturbances of the steady state, erratic as well as regular, do not leave any residual and cumulative effects, and after each disturbance the system returns to the same ground state.

The lasting and more profound changes in soils are caused by environmental changes of a different kind—for example, the climatic changes in the Pleistocene. Such changes could not take place without being accompanied by equally great changes in vegetation and in the character and the rates of erosion and sedimentation. These interdependent changes in all determinants of the

soil's steady state necessitate a simultaneous adjustment of the soil to the new conditions. If changes in the environment are slow enough, then readjustment of the soil proceeds hand in hand with them, and at no time is the soil out of equilibrium with the surroundings. Catastrophic changes, however, might leave the soil temporarily out of balance, and reestablishment of balance requires a certain amount of time.

The ability of the soil to readjust itself to the changing environment was recognized by the pioneers in soil science, who established several cases of striking changes in the character of soils and concluded that soils are capable of evolutionary development. Ideas about soil evolution proved to be quite popular, although they are clearly an outgrowth of the influence of the same philosophy of the biological sciences which was mentioned above. Followers of this school postulate that time is the fifth essential determinant of soil formation and that the character of soil changes merely with the passing of time, even if all other determinants remain constant (20). The offspring of this postulate is the theory of soil ontogeny and ages, such as youth, maturity, and senility.

Equilibrium constants of soils in a steady state vary from place to place with local conditions. These soils differ from one another in some chemical as well as morphological characteristics. The differences might be in kind or only

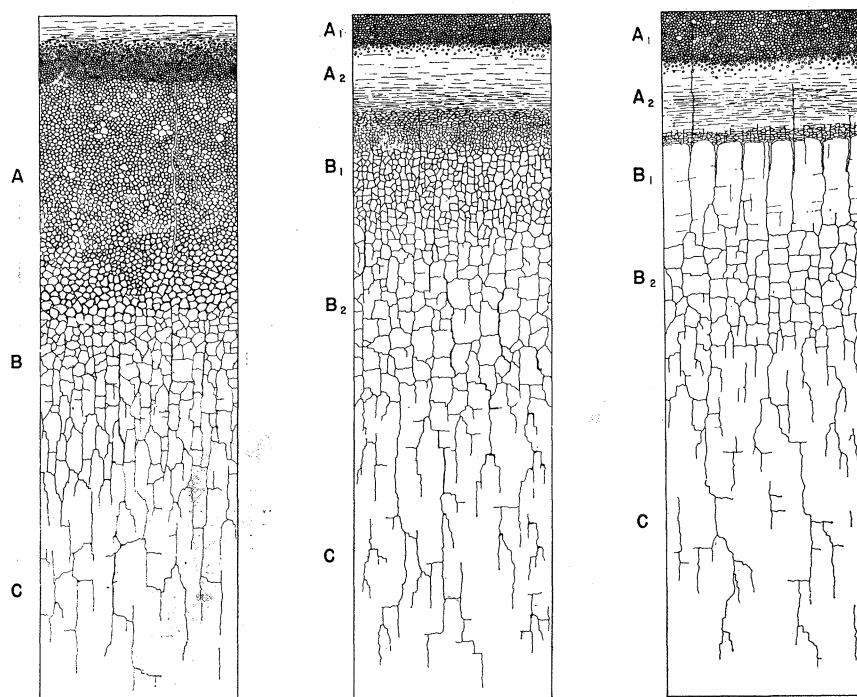
in degree—that is, qualitative or quantitative. A certain horizon might be present in one place and absent in another. Again, the same horizon might be, perhaps, twice as thick in one place as it is in another, and better developed. All such differences are due to some differences in local conditions. Notwithstanding these differences, each of these soils might be in a steady state, adjusted at every point to its specific environment. To interpret these local variations as representing different stages of soil ontogeny is hardly anything more than wishful thinking.

Time and space are elements of the essence of being but not factors in any particular form of being. Every material object occupies a certain space, but its existence is not caused by the space. Every change takes a certain time, but, again, it is not caused by mere passing of time.

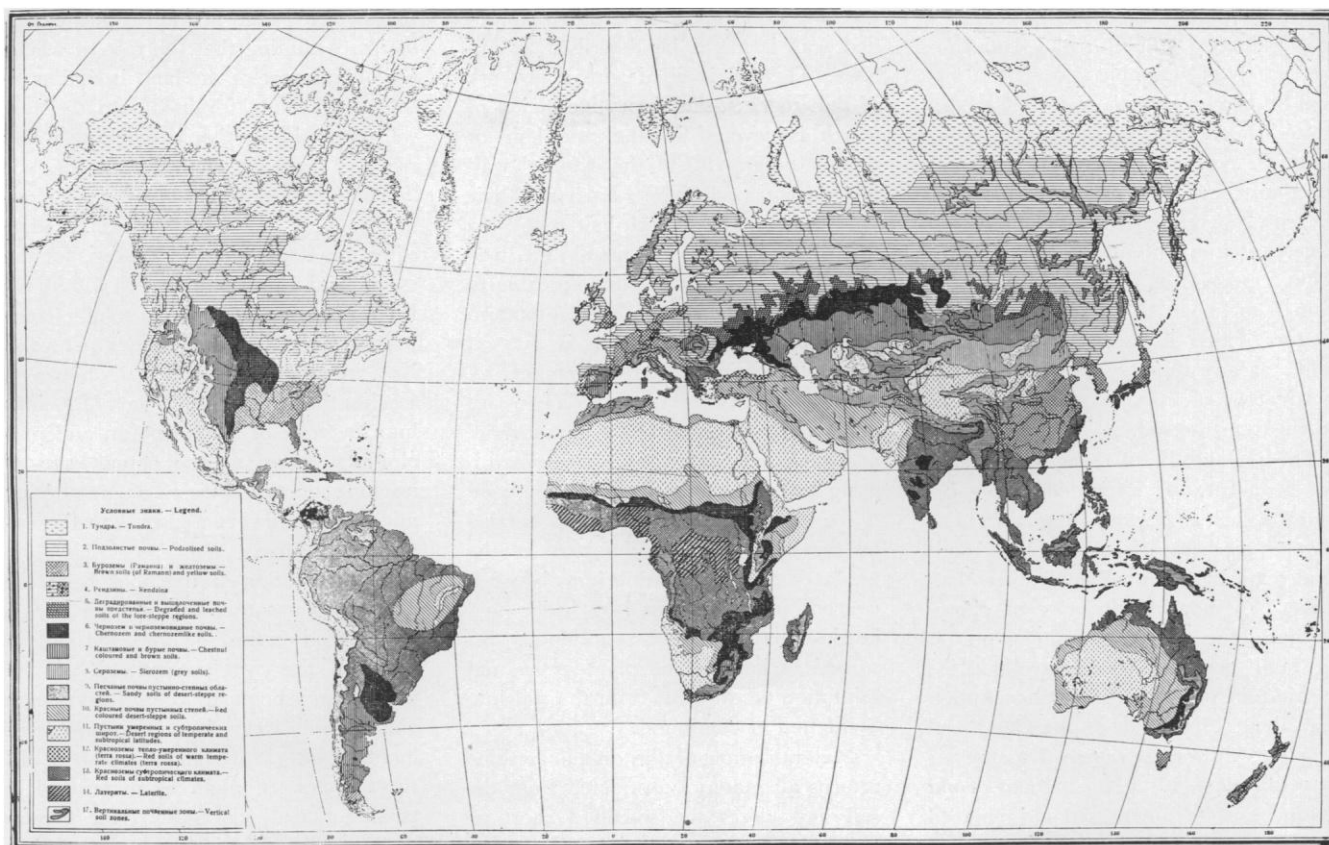
Dependence of soil upon the environment is so complete that evolutionary development of the soil would be possible only in unison with a similar development of the determinants of soil formation. As pointed out earlier, the environmental factors are not fixed, indeed. Their changes, however, are of a different kind (21).

Changes in climate do not lead to the development of some new types of climate which did not exist before. These changes consist especially of changes in mean temperature and rainfall in certain regions. There is no indication that there have been significant changes in solar constant during geological history. Hence, probably there have been no significant changes in the amount of evaporation from the earth's surface and the total rainfall on earth. Distribution of this precipitation over the earth's surface, however, is not fixed. Geographical distribution of cold and warm climates apparently also is changeable, even though perhaps not within such wide limits as the distribution of dry and humid climates.

The same holds true about land forms. Periods of accelerated mountain formations alternated with periods of peneplanation. A formerly mountainous land could have been leveled in one period, whereas mountains would rise on what used to be a plain, if not the sea bottom, in another period. But whenever mountains or plains have been formed, they have been just ordinary mountains or plains. There is no indication of the development of some peculiar, entirely new, land forms which did not exist in earlier periods.



Typical "structural" profiles of three different soil types. (Left) a chernozem; (middle) a podzol; (right) a solonchok.



Glinka's world soil map, a scheme of the global soil system (showing zonation of soils) which was discovered by V. V. Dokuchaev at the close of the last century. The northernmost zone is occupied by the primitive tundra soils. The next broad zone is the kingdom of podzolized soils, the most highly developed local form of which is the podzol. The third principal zone is occupied by the chernozems and closely related chestnut soils, followed by the boorozems of the subarid zone; this zone, in turn, grades into the desert zone. In the lower latitudes on both sides of the equator, all horizontal soil zones are distorted and partly eliminated by vertical zonation caused by relief. Each soil zone is characterized by a different equilibrium constant of its soil, corresponding in each belt to the zonal intensity of radiation, rainfall, and biological pressure. The map was published by Prassolov after Glinka's death, in *Priroda* (1928).

The same minerals and rocks have been attacked by the same physical and chemical agencies and altered in the same ways to yield the same products throughout most of geological history. Old clays and sand, no matter when they were formed, do not differ from clay and sand being formed now. Erosion, whenever it has occurred, results in the same sorting of loose rock waste and deposition of sediments. Again, there are no traces of the development of some new mineral or new kind of material.

Thus, changes in climate, land forms, and source materials are essentially changes in distribution over the earth's surface of certain types or kinds of these components of geographical landscapes. These changes cause readjustment of local soils to the different conditions, and thus redistribution of various soils over the land, but they cannot stimulate an evolutionary development of new soil species.

Only in the biosphere do we see a remarkable train of changes with time. These changes have been confined especially to forms of life. Probably there

were no great changes in the amount of life. Living matter has a seemingly insatiable urge for expansion and probably has saturated the geophysical sphere fitted for life from the beginning of its existence. Nor have there been any radical changes in the basic composition of living matter. The protoplasm of the amoeba does not differ from the protoplasm in the cells of the higher organisms.

The true causes of biological evolution still are unknown. Perhaps this process is driven onward by some powerful intrinsic impulses of living matter, rather than by external influences. This subject is beyond the scope of this article. We consider living matter in terms of its mass, its chemical composition, its energy, and its rate of renovation rather than in terms of morphology and individual organisms.

Biological pressure (22) is an essential factor of soil formation. Changes in this pressure, caused by changes in the density of generic composition of vegetation and other organisms, do disturb the steady state of the supporting soil and cause its readjustment. The latter, how-

ever, is merely a manifestation of the natural law (Le Châtelier, 19), rather than an evolutionary process, even if it has been triggered by the evolutionary change of its immediate cause.

Soil and Life

The soil is spoken of as a sort of bridge between the organic and mineral worlds (23). This bridge carries a two-way traffic. Plants obtain from the soil the essential elements without which the organic world would not exist, whereas organic residue returns the borrowed elements and brings, in addition, other elements, notably carbon and oxygen, to enrich the mineral framework of the soil. In this way some ions of calcium, potassium, magnesium, phosphorus, sulfur, and other elements temporarily withdraw from the pedogenic process, being captured by living matter.

The mass of living matter on land is of the order of magnitude of $n \times 10^{12}$ metric tons, where n is hardly more than 2 (24). The bulk of it is made

of nonlithophilic elements—oxygen, carbon, hydrogen, and nitrogen—and consists largely of vegetable matter. Not less than 80 percent of it is water. The “dry matter” makes up, on the average, from 20 to 25 percent of the bulk, and not less than four-fifths of it is carbon and oxygen (25). The “essential elements”—largely calcium and potassium—make up about 2 percent of the “green” mass, or from 6 to about 15 percent of the dry matter. Thus, living matter on land holds, at any time, some 3 to 4×10^{10} metric tons of essential elements withdrawn from the soil.

The average life of living matter cannot be accurately estimated. Some organisms, such as *Sequoia sempervirens* or *Sequoia gigantea*, live more than a thousand years, but many others live less than a day. To judge by the rate of photosynthesis, the turnover of living matter on land amounts to about 4.0×10^{11} metric tons per year (on the assumption that about 15 percent of the CO_2 fixed by photosynthesis is returned to the air by respiration (11)). This amount of old residue must be mineralized and replaced by fresh residue, so the same amount of living matter must die off, to be replaced by the newly formed proteins, carbohydrates, and so on. This replacement requires a passing through the living matter of about 10 billion metric tons of essential elements each year. On the average, for the entire land area, it represents the movement of about 6.6 milligrams of free ions per square centimeter per year.

Movements of essential elements, however, represent only a small part of the exchange between the soil and living matter. The figures given above do not include mobile carbon and oxygen, the combined mass of which is many times greater than the mass of all essential elements combined. Furthermore, living matter keeps in motion an enormous amount of water. In order to build 1 ton of dry matter, plants transpire more than 200 tons of water. Photosynthesis on land amounts to a production of about 4.0×10^{11} metric tons of vegetable material, and about one-fourth of it is dry matter. Production of this material requires transpiration by plants of at least 2×10^{13} metric tons of water, representing from 17 to 20 percent of the annual rainfall on land. These figures are not precise, indeed. Their purpose is merely to give some idea about the order of magnitude of the movements of matter between soil and living matter.

The mechanism of the transfer of free ions from the soil to living matter is not

yet fully understood. In a much simplified way it might be described as follows: The soil is filled with a network of thin rootlets, the absorptive region of which is covered by the root hair or tubular outgrowths of the external wall of epidermal cells (26). Each root hair (not to be confused with hair root) is a sort of sac made of the membrane, permeable to free ions but impermeable to colloids. Inside the sac are protoplasm and sap, whereas outside it is the soil solution containing ions of elements set free by weathering. In accordance with osmotic pressure, Donnan equilibrium, and various other factors, free ions migrate across the septum inside the root, to be absorbed by colloid and carried by the sap into the aerial parts of the plant. Thus, the equilibrium between concentrations of free ions inside and outside the root hairs is continuously disturbed as long as the plant grows and migration of free ions from the soil into living matter continues.

Mineralization of the organic residue returns all material abstracted from the soil and closes the so-called short or “biological” pedogenic cycles. The term *cycle* does not indicate that the same ions shuttle back and forth between soil and living matter. It means merely that certain quantities of ions are always on the move along this route. Individual ions continuously escape from the stream, but the vacancies are filled just as steadily by other ions of the same elements captured by the current.

The driving force of this never-ending migration is living matter. In this way living matter counteracts weathering. It has been pointed out elsewhere that the general trend of weathering is toward ionic dispersion of solid matter. Chemical denudation of the horizon of weathering tends to leach out from this horizon everything that might be carried away either in solution or in suspension. Living matter intercepts some of the mobile ions, incorporates them into organic tissues, and thus protects against leaching or dissemination in space.

The role of living matter in the geochemical process on the surface of the earth's crust is not restricted to the short pedogenic cycles. Large quantities of free ions are steadily removed from the horizon of weathering by chemical denudation. Clarke has estimated that all rivers carry into the ocean about 2735 million metric tons of dissolved matter per year, especially ions of CO_3 , SO_4 , and Ca (1). The area that is drained into the sea makes up about three-fourths of the whole land area. The remaining one-

fourth of the land is drained into closed basins. Assuming that the rate of leaching of this part of the land is similar to that of the land drained into the sea, we may estimate that percolating water removes from the land at least $3\frac{1}{2}$ billion metric tons of dissolved matter annually. This amount alone would indicate an average rate of leaching (for the entire land area) high enough to remove from 2 to 2.3 milligrams of soluble compounds per square centimeter per year. Not all dissolved material, however, reaches the sea. A certain part of it sinks into the zone of anamorphism and precipitates there, so the actual rate of leaching of the horizon of weathering might be somewhat higher than the figure given above.

The migration of free ions from the horizon of weathering into the ocean, into closed basins, or into the deeper layers of the earth's crust is a part of the long geochemical cycles. Information about these cycles is much more fragmentary and sketchy than that about the short cycles. It might be mentioned in passing that living matter, the greater part of which is in the ocean, has a hardly less active role in the long cycles than it has in the short cycles. This activity and its results, however, are outside the scope of soil science, which is concerned with only one link in the long cycles—that is, removal of free ions from the horizon of weathering.

Although the actual average rate of leaching of the horizon of weathering cannot be estimated with any degree of reliability at the present time, it seems fairly certain that, in short pedogenic cycles, living matter on the land keeps a quantity of mobile compounds greater than the amounts of annual loss due to leaching of these compounds. This is an essential feature of soil formation. Usually it is referred to as the accumulation of essential elements in the soil or the development of an essential (from the agronomical viewpoint) property of the soil, its productivity.

Here again the terms *accumulation* and *development* are misleading. A progressive development or accumulation could take place before a steady state is reached. After this, there might be some changes in this state of the system due to adequate changes in the environments, but there would be no further “accumulation.”

The concentrations of the mobile compounds in any part of the spatial soil system are determined chiefly by the requirement of the local plant community or—to put it in a more general way—

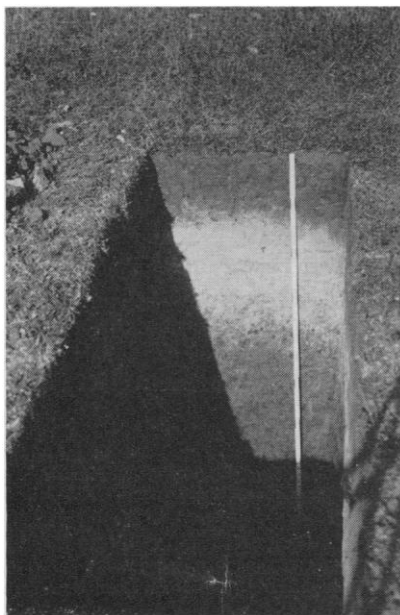
by the local biological pressure. Everything in excess of this requirement is likely to be leached. It might or might not be removed from the soil right away, depending upon the available means of transportation. In arid climates, for example, the rate of leaching might be too low to cope with the liberation of free ions by weathering; hence, some enrichment of the zone of weathering in these ions would result independently of, and sometimes even to the detriment of, local life. Such an enrichment does not go unchecked indefinitely. Again, its rate decreases exponentially until the steady state has been established.

Relationships between soil and living matter are mutual. Living matter maintains a fairly constant concentration of certain elements, the free ions of which would be leached out if there were no life. On the other hand, the biological pressure at any particular place is determined by certain local factors, among which the rate of release of essential elements in available form is one of the most important.

Close interdependence between the soil and living matter has led to the theoretical assumption that soil formation begins with the introduction of life into the process of weathering and, thus, to differentiation between abiotic weathering and soil formation proper. This differentiation is rather academic. The very idea of abiotic weathering is quite vague and perhaps rather groundless, inasmuch as the origin of life on earth is still a mystery (27).

All essential determinants of soil formation vary from place to place, and nowhere is any one of them quite uniform over a very large area. Thus, the soil might be in the steady state at various particular points, yet this state would not be the same under different local conditions. Soil taxonomists use these local differences in the general character of the soil as criteria for differentiation between individual soil species, although the very concept of soil species is vague. Perhaps this concept is just another example of the influence of the biological sciences.

Local differences indicate that soil formation involves not merely a differentiation of genetic horizons, giving to the soil a certain morphological profile, but also differentiation in a horizontal plane, which makes the soil a patterned spacial system. Dissection of this system on the basis of ill-defined and wholly abstract soil species might serve some practical purposes but has no scientific basis or justification.



A soil pit. Investigation of soil anatomy requires transection of the soil; this should be regarded as a sort of surgical operation. One carefully and properly made transection provides more information about the make-up of the soil system than scores of amateurish holes hastily made in routine soil survey. The sorry state of genetic soil classification is due especially to the lack of precise information about the object of classification.

Soil science is passing through a difficult stage in its development. After a promising start at the end of the last century and the beginning of the present one, it has been plagued by formalism and has lost much of the original impetus. The aftermath of the two world wars and widespread social upheavals put severe stresses on world agriculture, and soil science, which is still oriented toward agronomy, was called on to concentrate on purely practical problems dealing with the betterment of crops. Research in basic science was forced to surrender priority to sheer technology and soon found itself in the strait jacket of bureaucratic supervision, and its methods of scientific inquiry were largely replaced by sadly unimaginative empiricism.

The same stresses of the last few decades generated an almost explosive surge of other sciences, notably physics and chemistry, which almost overnight outgrew their classical realms and began to deal with the cosmos.

For the time being, agronomy is left far behind, but, indeed, it cannot stay behind too long. The growing population demands more of the essentials of life, and the time is rapidly approaching when our classical agriculture will be unable to cope with the demand.

The prime object of agriculture is to capture solar energy in forms specifically adapted for human consumption—that is, to yield a crop of certain plants, such as cereals, fiber plants, and forage grasses. The amount of energy from the sun's rays which might be captured by plants is determined by the solar constant. By far the greater part of this energy is consumed in maintenance of an environment in which photosynthesis is possible—that is, in evaporating a sufficient amount of water, heating the atmosphere, and keeping weathering on the steady run. Only a precious small part of this energy is available for photosynthesis itself, and this part determines the amount of living matter which corresponds to the saturation of the biosphere by life. Hence, it is not likely that a significant increase in captured energy might be achieved by raising the rate of photosynthesis. It is more likely that future agriculture will have to replace a much greater part of the wild vegetation and low-yielding plants by plants capable of yielding more proteins, starches, fibers, and so on per unit weight of vegetable material. This means rather drastic meddling with the driving force of the short geochemical or pedogenic cycles and might lead to disastrous results if it is undertaken without a thorough understanding of the process.

The soil has been defined rather figuratively as a sort of turnstile through which passes an endless stream of free ions of various elements, making up the short and long geochemical cycles. In its infancy soil science could do little more than stand at the turnstile and observe the morphological effect of the process. Now we can count passing ions and analyze the process quantitatively. In the future we hope to be able not merely to analyze the process but to control it and direct the currents of matter and energy into predetermined channels. An entirely new, man-made mechanism for capturing the energy of the sun's rays will be the contribution of soil science to the age of the mastery of atomic energy and the conquering of outer space.

Conclusion

Current research in basic soil science is somewhat handicapped by the lack of clear-cut differentiation between the problems and aims of the pure and applied branches of this discipline. Applied soil science deals largely, if not exclusively, with the soil-and-plant relation-

ships in their agronomic aspect. Pressing practical problems and the ever-present natural urge for higher standards of agriculture allow the applied branch to dominate the whole realm of soil science. The methods of applied science, however, usually are rather crude and entirely inadequate for a basic research. Therefore, one of the first problems to be solved is that of freeing basic science from the burden of practical tasks. This is not to say that these tasks are unimportant or could be laid aside, but merely to point out that the basic facts, which after all are essential for the quickest and most rational solution of these tasks, might be discovered sooner if research were freed from utilitarian orientation.

Our second problem is to develop an adequate technique. A mere scratching of old cliffs and road cuts for study of soil anatomy or a collecting of samples for chemical analysis served the purpose in the pioneering stage of soil science. It still satisfies the requirement of a routine soil survey, but it is no longer adequate in scientific investigation. Chemical and physical analyses of soil are adequate insofar as procedure is concerned, but methods for interpretation of the results and especially for coordination of various analyses and selection of proper material for laboratory study are in urgent need of radical improvement.

Careful study of soil morphology is an essential prerequisite for the identification of the soil and the collection of samples for analysis. Morphology as such, however, is just an empty shell if its origins are unknown. Hence, the need for a shift of attention in soil study from a descriptive morphology to study of the genesis and dynamics of soils is clearly indicated. Such an orientation of soil science was foreseen by the pioneers (Dokuchaev, Shaler, and others) but later on was overshadowed by practical considerations.

Soil genesis and the pedogenic process still are defined differently by the different schools of soil science. In some schools, the concepts of soils and their functions are still influenced by the theoretical assumptions that soils are somewhat akin to the living bodies and that soil science belongs to the realm of biology rather than to the family of earth sciences. A critical review of these concepts in the light of geochemistry and geophysics is the order of the day.

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16. S. A. Waksman states that certain grassland soils contain more than 10 percent of humus, the carbon content of which is in the neighborhood of 56 percent [*Humus* (Williams and Wilkins, Baltimore, 1936)].
17. V. I. Vernadskiy states that "the amount of living matter, presumably, represents a planetary constant since pre-Cambrian time. Undoubtedly, this constant is subject to fluctuations. It defines the totality of cyclic processes and reversible phenomena represented as the state of dynamic equilibria. This constant is of the same order as the constants of mean composition of the atmosphere or salinity of sea water" [*Ocherki Geokhimii* (outline of geochemistry) (in Russian) (GIZ, Moscow and Leningrad, 1927)].
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