SOIL : THE ENVIRONMENTAL INTEGRATOR

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ABSTRACT

Soil is defined in terms of dynamic circulation patterns of water, air and minerals driven by solar energy. The soil is the reactor and exchanger of energy and matter and, as such, is the terrestrial environmental integrator and supporter of life on Earth. The environment as expressed in this context is a permeable membrane which shapes life forms, with an inherent capacity and resilience to function and respond to stimulii. Soil is an open and metastable thermodynamic system. It functions because of an external energy supply. The soil is remarkably resilient but its capacity and resilience are limited. Although soil is important for plant production for agriculture and forestry, its role in Nature is more vital in fundamental earth processes and moderating the effects of human manipulation. The soil is finite, scarce and fragile. Human activity may affect the soils' capability to function as an environmental integrator and moderator, if rates of human interference are greater than the rates that sustain soil processes.

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1.1 INTRODUCTION

Earth, fire, water and ether were espoused by early philosophers as the element (substance), component, feature or principle of a thing, a basic part and a constituent of all physical matter. Further, any of these substances were thought of as the natural (physical) environment of living things. If one modernizes the words of the early philosophers, the four elements may be called soil, energy (solar?), water and the atmosphere. It was the belief of the early philosophers that these four substances were the key to the planet Earth and to its unique characteristic as a living entity.

Lucretius (99-55 B.C.) illustrates the prevailing scientific concepts before the beginning of the Christian era in Book V, "On the Nature of Things". He states:

> "First of all, since the body of the earth and water and the light breath of air and burning heats, out of which this sum of things is seen to be formed, do all consist of a body that had a birth . . . the world must be reckoned of like a body . . . parts of the world are destroyed and begotten anew . . . there has been a time of beginning and there will be a time of destruction."

Lucretius anticipated our concept of Nature's Laws that were formulated several thousand years later as the Laws of Thermodynamics. He goes on further to speak of soil:

> "Part two of the soil is put under water by rains, and rivers graze against and eat into the banks. Again whatever increases something else, in its turn replenished; and since beyond a doubt earth the universal mother is found at the same time to be the general tomb of things, therefore you see she is lessened and increases and grows again."

Sir Francis Bacon (1561-1626), in describing a new methodology in the experimental interpretation of nature (Novum Organum), stated:

> "Now the empire of man over things depends wholly on the arts and sciences. For we cannot command nature except by obeying her."

Although humans have progressed immeasurably in art and science since these concepts were promulgated, their fundamental truth and simplicity begs one to reflect on their significance. Have the fundamental Laws of Nature changed because humans have devised complex institutions, elaborate language (including mathematics), and a better understanding of Nature? This question cannot be answered unequivocally, precisely or simply. Basic human behaviour has not altered much through time. Human ingenuity has replaced labor and toil with substitutes ever since the first human discovered fire or used a wooden stick to till the soil. Humans have had, and continue to possess, greater capabilities to destroy and kill than to save and nourish their own kind. Consider for example the expenditures in resources that are allocated to military endeavours because of the perception that our life-styles may be altered or changed and compare this to the amount of financial resources that are utilized for the existence (not change) of Homo sapiens and, in fact, life on Earth. Thus, although the sophistication and magnitude of human behaviour has changed, basic human behaviour has not, just as the fundamental Laws of Nature have remained.

If one reflects on the ancients' perception of earth, fire, water and ether, these four elements have a common feature. They are what economists and legislators term the "commons" (common property or common pool resources). There is little doubt that without the intricate interaction of soil, solar energy, water and air, that life as we know it could exist on Earth. Things that seem plentiful are little appreciated by humans, until one or more facets becomes limiting to the needs, wants and desires of humans, either individually or collectively. Personal health is taken as given, until one becomes ill; personal finances are paramount until bankruptcy; life is of incalculable value until death; and soil, energy, water and air are common goods (priceless and essential) but until their quality or quantity are exhausted, not worthy of concern. All things, the Universe, the Earth, and living entities have a beginning and an end. Laws of Nature and Time govern our environment and thus our very existence. Although heralded authors (Hardin 1968; Leopold 1949) have brought attention to these issues, little change has been implemented by society. We continue to use soil, air and water with little respect for their essentiality.

1.2 ENVIRONMENT

There are many usages of the concept of environment. We hear of the physical environment, the cultural environment, the social environment, the biophysical environment, the economic environment, the political environment and even the sociopolitical economic environment. In recent years environment has become an increasingly popular cliche employed by individuals, private groups, public servants, politicians and educators. The concept has taken on even more interesting interpretations since the publication of the World Commission on Environment and Development report on "Our Common Future" (W.C.E.D. 1987) and with it the popular concept of sustainable development, i.e., "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (W.C.E.D. 1987:43). Many people have embraced the concept to reinforce their beliefs or actions. It is not uncommon to read such phrases as "sustainable economic development" or "sustainable socio-economic development" and, in an attempt to capture all audiences, "environmentally sustainable socio-economic development". This is but one example of how humans utilize language and pragmation to justify their own needs and promote their singular beliefs and adherence to neoclassical dogma. It is an attempt to explain human activity as being rational and in concert with ones own view of Nature.

In an attempt to avoid catapulting into the above abyss, I choose a simple definition of environment: the membrane that shapes life into the form in which it exists. The attributes of the membrane are defined in operational terms by which we categorize the continuum of Nature. Central to this definition, is that the focus is on the phenomenon of life, as we know it on Earth. If we accept this simplistic, somewhat vaguely defined, concept of environment, as those intrinsic properties and values that shape the existence of life, it becomes evident that a living thing is affected and responds to its environment. If response and adaptation of the living entity to its environment is too slow, the living thing will perish. This brings into focus the element of time.

While human populations were small, humans could live with their natural (physical) environment and be shaped by this environment. The environment did little to directly alter the living thing and life-forms adapted to the changes in the environment or became extinct. Homo sapiens being largely unspecialized are highly adaptive life-forms to different environments; from forest to grassland to alpine to arctic. Homo sapiens also possess the ability to modify their environment, unlike most other animals, by the use of tools and energy (fire). As human populations grew, became more social in behaviour, and developed their ability to modify their environment for their own needs and desires, they increasingly changed the very environment that had shaped them. The Earth's permeable skin of soil, water and air is the environment of man and all living things. It is this environment that provides water, oxygen, food and shelter; the necessities of life. Homo Sapiens, however, demand more!

The brain allows the species to gain power, to gather resources from the environment far in excess of those of their biological needs. Early humans extracted from the atmosphere only the oxygen that was required for respiration; today humans extract oxygen not only for life but to support combustion, factories, extraction and processing industries. The resulting production of gases, such as carbon dioxide, appear to be far in excess of those that can be assimilated by the Earth's natural photosynthetic machinery or by the oceans and similar sinks. Technology has shifted the balance between demand and supply, and increasingly is introducing new and foreign things (synthetics) into Nature's system. Take, for example, the application of fertilizer technology to replace or augment the basic nutrients for crops in agriculture or forestry. Inorganic forms of fertilizers, such as nitrogen, dramatically increase crop production but impoverish the soil in organic carbon, which in turn affects the physical properties of the soil. Resulting changes in soil physical properties, in turn, affect the balance of the interrelationships between air and water in the soil, making the plant less efficient in utilizing the added fertilizer (Young 1989). The unused fertilizer, if soluble such as nitrogen, leaches into groundwater, streams and lakes, which through contamination or overproduction of aquatic plants renders water unacceptable for human consumption (Greenland and Hayes 1981). In addition, microorganisms which function in the natural process of nitrogen fixation are disrupted by additions of inorganic fertilizer nitrogen (Brady 1990). Thus, nitrogen fixation slows or ceases and certain of these microbes may be unable to survive. The growth of plants therefore becomes increasingly dependent on nitrogen fertilization. Possibly more significant is that fertilizers (and other materials added to soil) may deplete the natural populations of nitrogen fixing and other organisms. As has been shown, the effectiveness of this symbiosis is microbe and plant species specific. Current management agricultural practices may be eliminating varieties of organisms that could overcome total dependence on inorganic nitrogen fertilization. Thus we are using up the biological "capital" of the environment and may be destroying the capability of the soil to recover (Hillel 1991).

Haberen (1991) argues that a "soil health index" is needed. He states that "soil quality is like the weather. People talk about it, few understand it, and still fewer do anything about it." Haberen argues that soil biology remains a "virtual unknown" and hypothesizes that losses of species at the far end of the food chain may be less important to the world's ecosystem than those species at the start of the living chain, the living soil.

The addition of foreign materials to soils such a synthetic plastics, chemicals or sludges may exceed the assimilative capacity of the soil. One may argue that side-effects of any management scheme are to be expected in order to gain from that management, usually in terms of economic return. The point, however, is that human's abilities to modify, manipulate and possibly destroy the capability of the environment may exceed the time frame to remedy or reverse any undesirable side-effects. In fact, the above discussion mandates that as humans modify their environment to meet their needs and desires, they must in fact have a much better understanding of the Laws of Nature, than when the natural environment merely shaped their lives; for by modifying the environment, humans in fact are shaping themselves and ultimately influencing their destiny.

Most of us today were educated in a fashion that is popularly termed as reductionist science. We are the product of the era of the specialists, drawing imaginary yet largely impermeable boundaries between perceived segments of Nature's continuum.

Descartes (1596-1650) in Part II, "Discourse on Method" gives four precepts of logic:

> "The first was never to accept anything for true which I did not clearly know to be such . . . avoid precipitancy and prejudice . .
>
> The second, to divide each of the difficulties under examination into as many parts as possible, and as might be necessary for its adequate solution.
>
> The third, to conduct my thoughts in such order that, by commencing with objects the simplest and easier to know, I might ascent little by little . . . to the knowledge of the more complex; assigning in thought a certain order . . .
>
> And the last, in every case to make enumerations so complete, and review so general, that I might be assured that nothing was omitted."

Humankind has oscillated between the extremes of holism (e.g., Gaia) and intense specialization. We hear criticism of today's educational system as being too specialized and that more generalists (often equated with better educated rather than trained) are needed. Neither extreme has been shown to be satisfactory. Society should seek a balance of both approaches in order to meet the magnitude of issues and concerns facing our increasingly complex institutionalized world. We need to strive for a balance of views and approaches to science rather than intellectual snobbery of singular alternative approaches espoused by one group or another.

Relatively recently the literature has abounded with questions of scientific ethics. Collins (1991) cites three components of ethical thinking: the recognition of (a) intrinsic values in nature; (b) the instrumental or utilitarian effects of decision making on human welfare; and (c) the long term consequences of behaviour that may be unsustainable. Ethics, therefore, is dependent on time and circumstance, which govern choice. Growing populations, education and scarcity of resources will alter ethical judgements. Here too, humans can take advantage of their intellectual capabilities and technologies to aid in achieving the goals of improving human perception and behaviour by the employment of the extension of the human brain, the computer. Computer technology and application can assist people to better understand the complexities of Nature both with human and without human interaction. This process must be conducted with perception, caution and care. The utilization of computers must be regarded as a tool of science and humanity, and not an end in itself. Like the human brain, today's computer is limited by the information available, the understood relationships among pieces of information, various perceptions and bias inherent in the information, and the situation (time) under which the facts of Nature's system were collected.

Concern about the environment and the survival of the human species is not new, nor will society refrain from expressing concern about the environment that shapes their lives. Over time Malthusian philosophy developed advocates and skeptics of equal conviction. Resource economists such as Krutilla (1972) and Pearse (1992) argued that technological progress broadened the resource base on which humans depend so that the scarcity foreseen by Malthus has not materialized. Rather than argue the nuances of

Malthusian philosophy, it is more constructive to view resources and the environment in terms of Nature's Laws. As Loehman and Conner (1974) pointed out almost three decades ago, environmental quality arises from the use of resources; the key problem is scarcity, i.e., both resources and the ability of the environment to restore itself are limited. Neo-classical economists focus only on resource availability, neglecting the inherent temporal limitations of the environment to restore itself.

A crucial issue that has been more vividly popularized in the past few decades is the ratio of human population to resources and the shifting of that ratio regionally on the globe. Rising demands for resources make increasing demands on the environment, parts of which deteriorate while others are enhanced for human use. Holgate and White (1977) identified four key processes essential for environmental maintenance:

1. conversion of solar energy into chemical energy;
2. the biogeochemical and hydrological cycles by which essential mineral nutrients are passed through the biosphere to sustain plant, animal and human life;
3. the processes of organisms achieving complete life cycles and adapting by evolution; and
4. the perception, communication, processing and transmission of information to allow all living things to interact with each other and their environment.

It is within these perceptions that I wish to discuss soil: the environmental integrator. By necessity and choice, the following will be largely restricted to the natural (physical) environment, rather than the "socioeconomic-political and cultural environment".

1.3 SOIL: THE ENVIRONMENTAL INTEGRATOR

If one accepts the definition of environment, as in common usage by ecologists (including human ecologists), as "the unique skin of soil, water, gaseous atmosphere and organisms that covers the planet", and incorporates the beliefs of the ancients of the four fundamental substances (elements) that are essential for physical matter (including human life), this may be schematically presented as a mechanical model shown in Figure 1.1.

The three interacting phases of the environment; solid, liquid and gaseous, driven by energy from the sun, give rise to soil and terrestrial life as we know it. It is at the points of interaction of the various circles that life begins and ends. It is this envelope that depicts the region in which life can function. As the static and mechanical model (Figure 1.1) attempts to illustrate, life is not a single point but a spatial area with various amounts of air, water and minerals. These interact to give rise to various combinations of living habitats or niches in the terms of ecology, ranging from almost all air, almost all water, to almost all mineral. Each component of the environment by itself is devoid of life. It is at the intersection of the environmental components that life exists, e.g., air and water (viruses); water and mineral (anaerobic organisms); mineral and air (chemoautotrophs). Of paramount importance, to have a functioning environment, is energy.

Attention is once more brought to the spatial envelope identified by soil sustaining life. The spatial area has boundaries among the three essential components. The region within the envelope may be termed the carrying capacity of the system, and the resilience of the system or its buffering or tolerance. Once these characteristics are exceeded: e.g., no air, no water, no mineral (no equating to both quantity and quality); the soil system collapses and life ceases.

The components of Figure 1.1 are dynamic and cyclical. During this process there is the opportunity to renew or rejuvenate the component and hence the system to a degree. Some cycles are relatively short (atmospheric circulation), others intermediate (hydrologic cycles), while others are of long-time durations (tectonic cycles). One can see from the diagram that there are interactions of phases, of the components in an open system driven by an external source of energy (that is, it is a thermodynamic system). Each component has intrinsic attributes that are defined, finite and have tolerable ranges (resilience) within which each operates. Extrinsic attributes arise from the interaction of components on each other (the environment). The shaded portion is the soil, the physical environmental integrator. It is also the realm wherein the vast majority of life both in terms of numbers and diversity are found. Cairns-Smith and Hartman (1986), as an example, argue that "life" originated on land, not in aqueous environments as is commonly held; with the clay minerals providing the template for molecular organization. Both "biological life" and "soil life" are

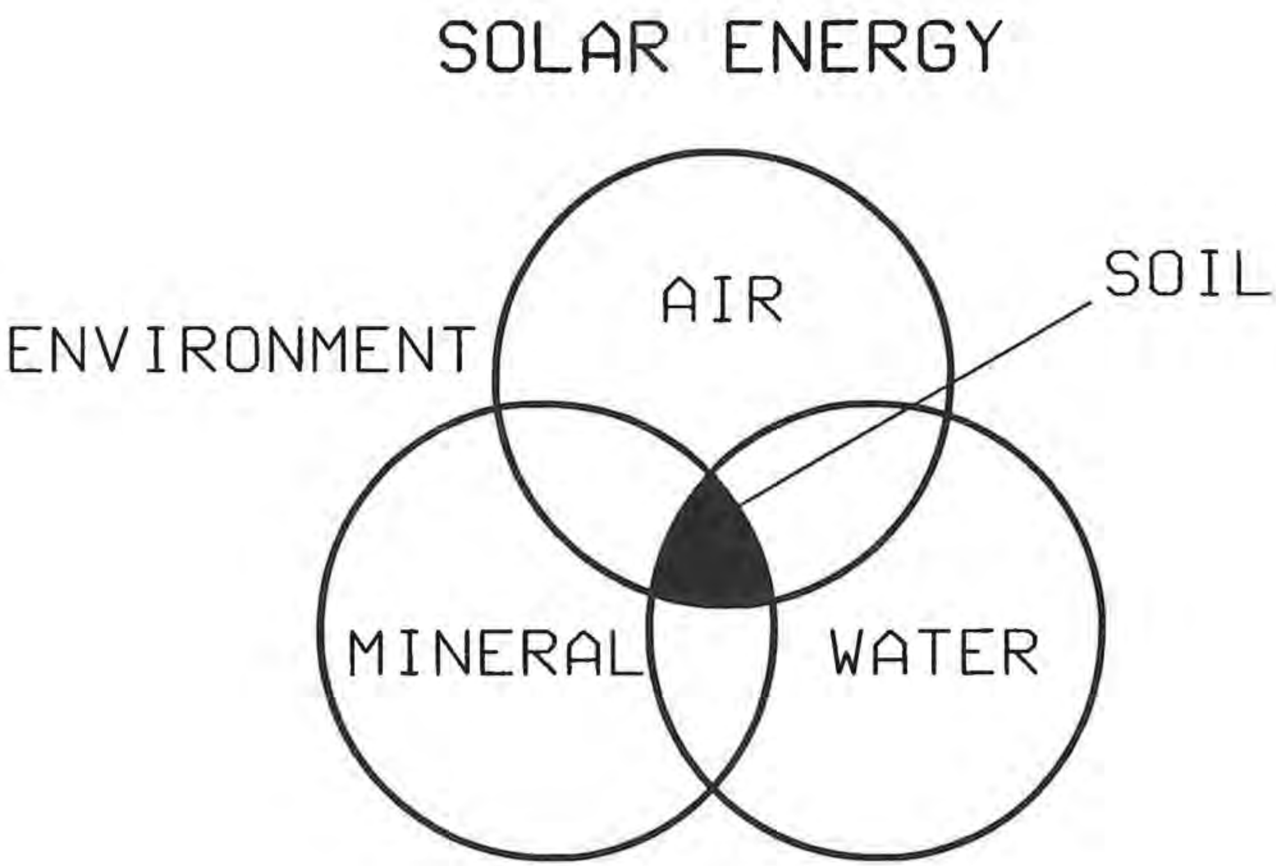

Figure 1.1 Conceptual diagram of the physical environment.

open systems and in terms of thermodynamics, unstable. The reason they exist and function is because of the external energy received from solar energy, which is converted to chemical energy and in turn allows work to be done.

1.3.1 Development Concepts and Models

Science has long recognized soil as a natural body. Joffe (1949) quotes Vernadskii as defining a natural body as "any object in nature which attains the status of individuality, endowed with an independent existence, capable of being distinguished and isolated from its environment, with an internal constitution, and controlled by specific laws in nature". Whether Fallou, Thaer, Dokuchaev or some other nineteenth century scientist is the founder of soil science as a discipline is of historical interest and debate. However, it was the school led by Dokuchaev that developed the concept that the principles applied in elucidating the natural sciences such as botany and zoology are applicable to the study of soil. This school looked upon soil as a distinct organism, with defined morphological features and inherent compositional character, with physical, chemical and biological make up. "The pedological method of the study of soil is analogous to that used in other sciences: chemistry, physics, and biology " (Joffe 1949). Joffe goes on to quote from Dokuchaev:

> "The parent materials which have undergone changes by the mutual activities of air, water and plant, I call soil. Soils are the surface mineral and organic formations, always more or less colored by the humus, which constantly manifest themselves as a result of the combined activity of the following agencies; living and dead organisms (plants and animals), parent material, climate, and relief."

Thus soil is different from geology or geological formations in that soil is distributed over the Earth by natural laws that govern living things. Each climatic type has a definite flora, fauna, and soil. Geologic formations are distributed with no definite relation to the climatic conditions of the region.

Natural scientists have recognized the soil as a product and part of nature. The early writings of Dokuchaev challenged many earlier utilitarian and pragmatic approaches to the study of soil. The classical book by the late Professor Hans Jenny in 1941, Factors of Soil Formation, has had a tremendous impact upon the manner in which we study soil today.

The so-called factors of soil formation (parent material, climate, biota, topography and time) in fact form the integrating model of the environment at the Earth's surface that results in soil and terrestrial life. The model of Jenny was conceptually sophisticated and modified by others to help explain their approach to the natural world (Billings 1952; Crocker 1952 and others). This conceptualization has brought debate and scientific enquiry about independent and dependent factors; of attempts to evaluate the effects of single factors on soil evolution (e.g., toposequences, chronosequences); and the application of semi-quantitative and quantitative methods to understand and predict soil history and evolution (chronofunctions, biofunctions). The success of unifactoral approaches has been disappointing because the factors themselves are not independent and covary. However, Jenny's formulation of the Factors of Soil Formation spawned and nurtured reflective enquiry (science) in soil-environment studies for over one-half a century. In this sense, Jenny's contribution to natural science has extended far beyond his writings about soil or pedology. The stimulation of others, provoked by Jenny's work, to adopt, refute, adapt, modify, quantify, redefine etc. has been one of the greatest contributions to natural earth science.

As an aid to help visualize soil as a fundamental and natural entity, one may consider the analogy of the soil as a living organism — a body. In this analogy, generalized and simplistic similarities are stressed, recognizing that there are fundamental intrinsic differences between the soil and a living body, in the sense in which humans understand life.

A body is the result of inherent characteristics (genetic make-up) and modified characteristics resulting from the body's surroundings (environment). A body occupies space, is a physical entity and has shape (morphology). In other words, a three-dimensional thing in nature that has intrinsic and extrinsic characteristics (properties). The body is contained within a flexible membrane and as such can vary in size and shape within limits governed by its intrinsic properties. This membrane is selectively permeable to the transport of energy and matter from outside and inside the body. The body is an open system. At any time there is an equilibrium or steady state developed between the inside and the outside of the body with respect to energy and matter. The body is composed of a number of inter-connected objects, called organs. Each of these organs has a unique shape and function. If the body is to perform effectively, each organ must function in an appropriate fashion. The appropriateness of the functional process varies within limits. If these limits are exceeded, the functional process slows and may cease. As this process within an organ changes so do processes in other organs change in response. If one organ ceases to function, this may lead to the cessation of the entire body. It is the process of exchange of matter and energy that allows a body to perform. In order to continue this performance, matter and energy must be continually added as the processes consume energy in their functioning (work).

The body has a capacity to carry out its functions (accumulative functions of its constituent organs) and a resilience or ability to return to its normal functions, if perturbed by "abnormal" or unnatural flows of energy or matter. If the unnatural flow is greater than the resilience, the organ (or body) decreases in its performance and may cease to function and the body dies. Some organs can be replaced if non-functional as a result of human ingenuity and technology. As a result, the body may function once again, usually at a somewhat lower level of effectiveness and a permanent scar is left that affects either the body's capacity to function or its inherent resilience. Often too, for the body to continue to function, outside additions of matter or energy (medicines) must be supplied. Rarely does the body regain its full potential to perform following such a perturbation. Thus, in order to have the body function at all, additional economic cost must be incurred.

So too the soil. The soil occupies space, has a morphology, has inherent or intrinsic characteristics (derived from the parent material), is affected by its surroundings (the other classical factors of soil formation), and bonded by a selective "membrane" that governs the flow of matter and energy through the so-called "open-system". The soil is meta-stable in terms of thermodynamics and thus is constantly changing and using up energy as work is done to affect these changes; yet at any instantaneous moment it appears to be in equilibrium (steady-state). The soil too, has "organs" and a concomitant array of processes which mediate interaction. The solid particles of various shapes, sizes and elemental composition; the pore spaces with their variable composition of gases and solutions; electrical charges; exchange phenomena of elements, aqueous constituents and atmospheric gases; and various combinations of solids, liquids and gases that interconnect all the parts. Thus each soil has an intrinsic hydraulic conductivity, cation exchange capacity, heat capacity, water holding capacity, permeability, etc. Each of these characteristics has a capacity and a limit or resilience imposed by the intrinsic and extrinsic characteristics of the soil.

Parts of the soil or the whole soil may cease to perform effectively if the capacity (quantity) or resilience (quality) of these "organs" are exceeded. The soil, like the body, has extraordinary capacity and resilience to the transfer of energy and matter. But each body has a finite limit. If exceeded, technology may rejuvenate or regenerate the soil to somewhere near its natural condition, but at a cost and usually with a permanent scar that decreases the original performance of the soil.

Although an understanding of the functions and processes of the parts is necessary, it is how they interrelate that allows the thing to function. This is as true of a life form as of soil. Reductionist science is important in order for humans to comprehend nature's organization. The re-introduction of the reductionist parts into the whole allows an understanding of how and why some part of the system functions and, just as importantly, allows us to predict functioning of the whole if a part is affected (or managed).

Human beings have been taking advantage of the soil's capacity and resilience since the dawn of the agricultural revolution; but, more importantly, they have increased demand on the soil throughout the Industrial Revolution. Today's environmental revolution is forcing human beings to rethink their expectations and demands on the body upon which their lives depend. The agricultural revolution took thousands of years to achieve, the Industrial Revolution a few hundred. Will or can the environmental revolution succeed in a matter of decades?

Homo sapiens may be on a collision course with the Laws of Nature. Some would argue that this type of scare tactic has been professed 1,000's or 100's or 10's of years ago and yet the human species continues to survive. They cite the fact that there are more healthy people today, with a longer life expectancy and with a higher standard of living than ever before in the history of human life (Pearse 1991) as evidence of the fallacy of Malthusian philosophy and the predictions of Limits to Growth (Club of Rome 1972). There are, however, more unhealthy people today living under poverty than ever before (Worldwatch 1992). The point is there are more people! We live on a finite planet if in no other terms than in terms of energy (required to do work to allow bodies to perform). Human populations are growing at exponential rates. Physical goods cannot grow forever, yet human populations appear to do so. It is not my intention to delve into the issues facing the future of Homo sapiens. The point is that the physical planet is finite, the energy (or matter) of the planet is finite, the environment is finite, as is the integrator of the environment finite.

The planet (and all things on the planet) was born, evolved and will die (cease to function). What we do not know with any precision or accuracy is when. This is controlled by the Laws of Nature. Our ultimate fate is known! As yet we cannot alter this fact by human intervention. The rate at which we approach that ultimate fate, in some measure, can be modified, that is we can affect the rate of the process or kinetics. If human intellect chooses rates at which process functions accelerate or speed up, the eventual end is reached sooner than if one chooses to work more closely at the rate governed by natural processes, or if by the application of intellect and technology, humans slow the rate without consequence. In terms of simple physical phenomena science describes this process on the basis of thermodynamics and kinetics. However, our understanding of thermodynamics and kinetics, especially as applied to natural things, such as soil, is most imperfect. The cliche that the "whole is greater than the parts" applies. We can analyze by rather sophisticated techniques the composition, structure and behaviour of a living organism, yet we do not understand the "magic", which some how arranged matter and energy into a myriad of unique forms and functions, called life. So it is with soil! We can analyze, mix the components and manipulate the mixture, but the soil is a natural body with intrinsic and extrinsic characteristics. It has unique functions and that it can exist and perform without human intervention is also "magic".

1.3.2 Thermodynamics and Kinetics

The planet is a bundle of energy. Our natural (physical) resources are energy provided by Nature, useful to human beings and governed by natural laws. The Laws of Thermodynamics are a set of rules conceived by science to describe the physical world. The First Law simply states that energy is neither created nor destroyed, although it can change form. Energy in this sense is the total of kinetic (motion) and potential (state) of the component molecules, atoms, and subatomic particles. This energy is an extensive property;

that is it depends upon the quantity of matter being considered and is independent of the path by which that matter was brought to that state. Any change in energy of a system as a result of a process results in work or heat. A system is simply a specified part of the universe which we have isolated for our specific purpose. If E represents the energy of a substance or system, then a change in energy ΔE is:

$$\text{State } 1(E_1) \rightarrow \text{State } 2(E_2)$$

$$\Delta E = E_2 - E_1$$

It can be seen that if work is performed and/or heat is generated;

$$E_2 = E_1 + q - w, \text{ and}$$

$$\Delta E = E_2 - E_1 = q - w$$

where q = heat and w = work

The above equations represent a reversible process, i.e., the conversion of State 1 to State 2 can be reversed by some external factor (in the case of soil by the addition of solar energy). A reversible process is one that may be visualized as consisting of a series of successive equilibria. Thus, to carry out a finite process reversibly requires an infinite time. Reversible processes yield the maximum amount of work (performance) that may be obtained for a net change in energy. When a process is not reversible, less work is obtained. An irreversible process can only occur when an external source of energy is applied. Soil and soil components are found in open and not closed systems and most processes are irreversible. Thus for the soil to function (to do work or perform) energy must be supplied. A process is only truly reversible if no heat or no entropy is produced. True reversible processes do not exist in Nature. There are processes where heat or entropy production is small, however, so we utilize the simplified concept of reversible processes in our deliberations.

Bohn and Bohn (1986) describe the application of thermodynamic concepts to natural soil minerals, which are impure and exist as solid solutions or contain isomorphous substituted components. These solid solutions dissolve nonstoichiometrically. They demonstrate how approximate solid activities in soil can be calculated and present modified solid activity coefficients for soil solutions. The proposed procedure is applicable to studies concerned with ion retention (adsorption), as well as coprecipitation and precipitation of solid solutions. This approach is most useful when one wishes to develop mathematical models to describe soil processes. Cosby et al (1986) have developed a mechanistic, process-oriented model on the effects of acidic deposition on the chemistry of drainage water to associated streams. The model incorporates thermodynamic considerations of anion retention, aluminum solubility, dissociation of carbon dioxide, cation exchange, and weathering. The authors stress the fact that such models must be viewed with caution, because calibrating and verifying the model requires long-term data and, possibly, a truly predictive model may not be necessary or feasible.

Richter (1987) describes the soil in terms of a reactor. He discusses the soil as a dynamic system, which entails the study of the interactive flows between a complex, arbitrary part of reality and its surroundings (environment). It is this investigation that reveals and expresses how a system behaves. Each system is by nature part of a larger system. An open system, therefore, is a natural, arbitrarily spatially limited entity which consists of elements or subsystems. As an open system, soil can only reach a stationary state, i.e., a system characterized by constant mineral composition, by minimum production of entropy and by maximum energy efficiency and minimum energy dissipation (Ulrich 1986).

The world as a whole may be considered a closed system and thus entropy can only increase. In open systems entropy can decrease by exchange of matter with its surroundings. Thus an open system develops or organizes (Morowitz 1968), structure, horizons, mineral-organic interactions, etc. For a more detailed discussion of these principles, the publication of Richter (1987) is recommended. He describes thermodynamic forces in terms of free energy, free enthalpy, and relates these to chemical potentials of gas, liquid and solid phases, and explains how moisture potential and nutrient potential can be formulated, for example in respect to plant nutrient availability.

All processes in soil may be viewed in a long term or short term perspective. Changes in composition (genesis) are long term, while function, e.g., crop production (utility) are of shorter term. Thus humus formation, podzolization, and the like are relatively complex and of long duration; while leaching of soluble salts, ion exchange, mineralization, compaction, etc. are less complex processes and are of a short time range duration.

Thermodynamics can only allow prediction of the final state of a system from a non-equilibrium beginning. It tells us little about how fast the reaction will proceed towards equilibrium or the reaction pathways that may occur during the transition. The rate of processes is termed kinetics. Kinetic studies are difficult to assess for even homogeneous systems; the complexities involved in heterogeneous systems, such as soil, are phenomenal. As Sparks (1989) observed:

> "Kinetics of soil chemical processes is one of the most important, controversial, challenging, enigmatic and exciting areas in soil and environmental chemistry".

Thermodynamics deals with equilibria: soil is rarely, if ever, at equilibrium. In an attempt to utilize kinetic concepts in the context of soil the environmental integrator, a brief overview of the Rate Law is introduced. By definition a rate equation is written as:

$$aA + bB \rightarrow cC + dD$$

Rates are expressed as a decrease in A and/or B concentrations (number of molecules or ions) or an increase in C and/or D concentrations over time. Thus if one monitors the change in A over time (t), the rate is:

$$\frac{-d[A]}{dt} \div a$$

or for C the rate is:

$$\frac{dC}{dt} \div c$$

or $$\frac{dC}{dt} \div c = \frac{-dA}{dt} \div a = k[A]^{\alpha} [B]^{\beta} \ldots$$

where k is the rate constant and α is the "order" of the reaction with respect to A, β is the order for reactant B and so on. The sum of the α, β, etc. give what is termed the reaction order, i.e.

$$n = \alpha + \beta + \ldots$$

Usually the reaction order, n, is determined experimentally.

Kinetic phenomena in soil can be described by apparent rate laws, mechanistic rate laws, or apparent, or mechanistic rate laws including transport processes. As an example, Stumm (1986) discusses the importance of surfaces and interfaces as they affect the composition of the environment. His examples of the oxygen donor atoms present on oxide surfaces as they undergo protolysis, form complexes with metal ions, or exchange for other ligands, show how these processes govern the rate of precipitation and dissolution of minerals, weathering of rocks and minerals, and heterogeneous nucleation. Chemical weathering is a key process in the neutralization of both internal production and anthropogenic input of acid into soil. The rate of chemical weathering in soil is a function of mineralogy, temperature, flow-rate, surface area ligand, CO_2 activity, and hydrogen ion activity (pH). Thus an increase in weathering rate upon an increase in hydrogen activity is not linear, thus increased soil acidification cannot be fully compensated by an increase in the neutralization rate in the soil. It is beyond the scope of this article to expand on these approaches. The interested reader is referred to Skopp (1966), Sparks (1986) and the more comprehensive volume by Sparks (1989).

One aspect that has significance to the discussion presented is the application of transition-state theory. The application of this theory often aids in understanding, or at least explaining, why a soil appears to be at equilibrium (steady-state) when in fact it is only metastable in the thermodynamic sense. Consider, for example:

$$A + B \underset{k_2}{\overset{k_1}{\rightleftharpoons}} (AB)^* \overset{K}{\rightarrow} C$$

where k_1 and k_2 are the rate of formation and the rate of destruction of the "activated complex" $(AB)^*$. According to this theory, the energy status of the activated complex $(AB)^*$ governs whether A and B will in fact form C. More useful perhaps is the equation:

$$\Delta G^\circ = -RT \ln K^*_{eq} = \Delta H^\circ - T\Delta S^\circ$$

where ΔG^o is the change in free energy of the reaction, R is the gas constant, T is temperature, ΔH^o is the change in enthalpy, ΔS^o is the change in entropy, and K^*_{eq} is the so-called pseudoequilibrium constant of the activated complex. [Thus K^*_{eq} is related to the more generally used thermodynamic state functions, i.e., the equilibrium constant K_{eq}^* is related to the thermodynamic state functions of enthalpy and entropy.]

The relationship discussed above is shown in the form of a diagram (Figure 1.2, adapted from Lavkulich 1969; Sparks 1986) where ΔG is the change in free energy, ΔG_1 is the free energy change as A + B react to form the activation complex (AB*) at rate, r_1 and ΔG_2 is the change in free energy as the activation complex (AB*) reacts to form C at rate, r_2. Thus, thermodynamic and kinetic considerations are related.

The amount of energy change to go from 1 (reactants) to the activated complex is commonly termed the activation energy. Once the activated complex is formed, the reaction can proceed. Whether a reaction will proceed depends on factors affecting this ΔG_1. If ΔG_2 is less than ΔG_1 the reaction proceeds at rate r_2. Catalysts may be present or added to a soil system to aid in the reaction rate. Common examples are the role of surfaces that adsorb reactants (e.g., colloidal clay or organic matter) allowing the adsorbate to remain in proximity to a surface and increasing the probability that an effective collision will occur and a new entity can form (Mortland 1986). In other words, the catalyst (surface) ensures effective collisions will take place. Enzymes and transition elements (Fe, Mn) are examples. On the

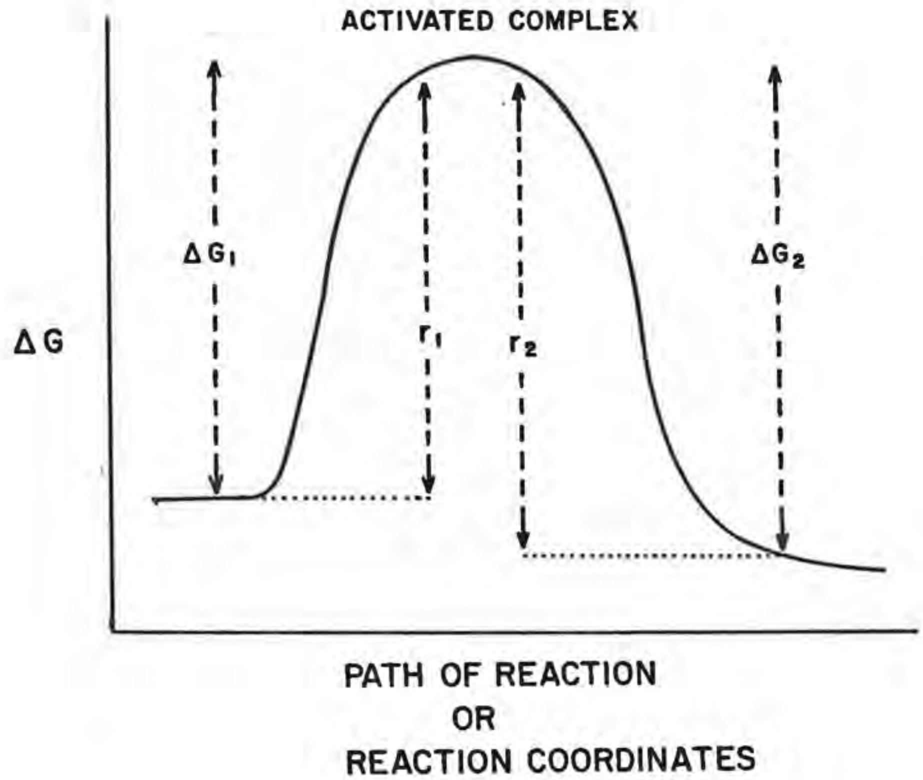

Figure 1.2 Generalized illustration of free energy changes.

other hand, soil systems have or may have added to them reaction inhibitors which slow reaction rates. Nitrogen mineralization rates may be slowed temporarily by certain chemicals or by the build-up of nitrite (Brady 1990). Heavy metals may inhibit enzymes by replacing the natural metal coenzyme (Tiller 1989). Most elements in soil cycle rapidly between soil solids, soil solution, organisms and the atmosphere, often faster than the rates at which they reach their most stable thermodynamic state. Thus the soil is thermodynamically metastable and the understanding of kinetics is becoming an increasingly important area of investigation in order to understand process and behaviour.

To obtain a better appreciation, the equation:

$$A + B \underset{k_2}{\overset{k_1}{\rightleftharpoons}} (AB)^* \overset{K}{\rightarrow} C$$

may be rewritten in the form:

$$\frac{-\Delta[A]}{\Delta t} = \frac{K[B]\,[A]}{K_m + [A]}$$

where k_m is the function of k_1 and k_2. This is illustrated in Figure 1.3. The equation for the curve in Figure 1.3b is represented by:

$$\frac{\Delta[\text{Rate Factor}]}{\Delta t} = \frac{\Delta[A]}{\Delta t}$$

This equation may be modified to express a variety of soil processes, such as the evolution of CO_2 from the addition of organic carbon, the appearance of nitrate from introduced nitrogen fertilizer, or the adsorption of water by soil colloids.

The above application of thermodynamics and kinetics is merely an introduction to the subject in order to show how one may predict the behaviour of soil as the environmental integrator. Thermodynamics and kinetic theory are only useful tools to aid in the understanding of soil processes.

These principles may be illustrated by the well known growth curve of microbial populations (Figure 1.4). Point 1 is considered the lag phase or in reference to Figure 1.2 prior to the formation of the activated complex (AB*); at portion 2 of the curve, the population grows exponentially (or the reaction rate is at r_1), until a steady state is reached (the activated complex (AB*) persists (position 3); gradually at first and then again exponentially death of organisms occurs because of environmental conditions (activated complex moves to lower free energy at rate r_2), and a new steady state is reached at 5.

The above generalized illustration gives an overall framework to the functioning of systems whether the system be simply two molecules reacting, the more complex growth of organisms, or the behaviour of a soil that has been subjected to externally induced factors. The Figure shows that there is a beginning and an end, r_1 and r_2 govern the time from birth to death, and region 3 illustrates the capacity of the system to function as a thermodynamically metastable system.

Another schematic diagram may aid in appreciating the approach (Figure 1.5). The areas under curves A and B are the same (capacity) but the rate at which X is achieved is different. Nature's Laws hold! Homo sapiens can control the rate (time) at which X is arrived at. Because the soil is an open-system, the areas under curves A and B need not be the same. Mineral weathering, N- fixation, fertilizers, airborne particles, etc. may increase the area. The area under the curve, however, is finite (capacity).

Harmsen (1992) illustrates the behaviour of Cd in soil following zero, first and second order reaction rates over a period of 200 years and the actual concentration of Cd found in soil at 56 years. He shows that depending on soil conditions, rates of addition or environmental parameters, the long term predictions regarding Cd sorption by soil varies. This demonstrates the strength of kinetic modelling that is both predictive and dynamic. It also shows that the same soil may behave differently (i.e., with different rates) depending on the driving force (environment). The shapes of the resultant curves fall between those presented schematically in Figure 1.5a and 1.5b.

REACTION RATE DEPENDENCE ON EXTERNAL FACTORS

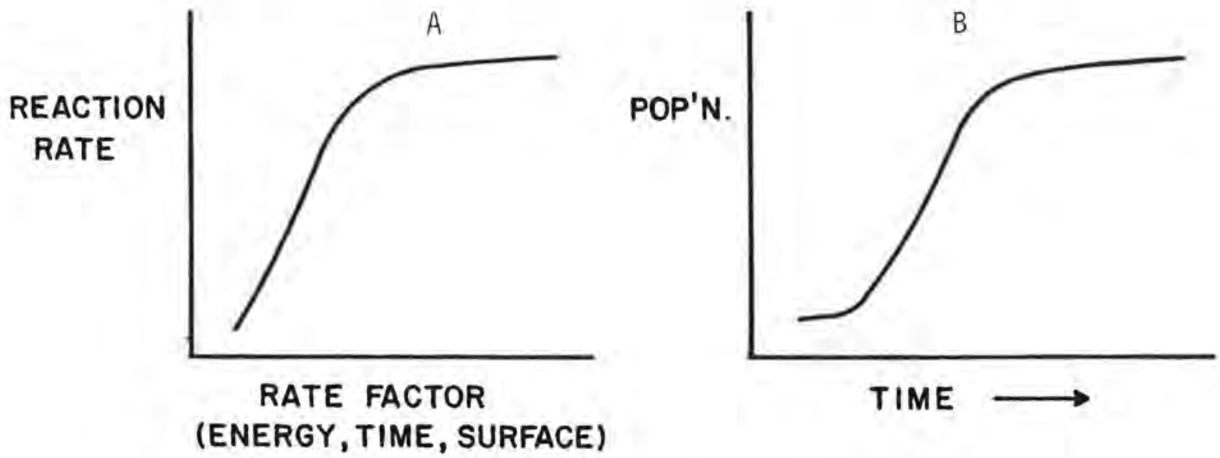

Figure 1.3 Reaction rate dependence on external factors (A) and analogy to population growth dependence on time (B).

GENERALIZED GROWTH CURVE OF ORGANISMS

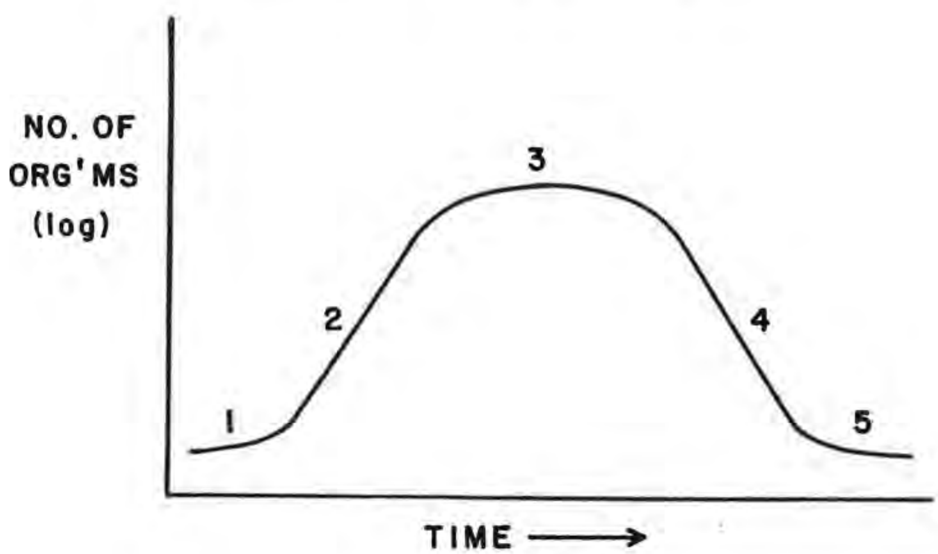

Figure 1.4 Generalized growth curve of organisms.

In my view, Malthusian theory holds. What society has been able to do by the adoption of technology is to increase the time interval until finite X is reached and thereby postponed the eventuality put forth by Malthus. The planet has a finite capacity. In terms of human life-span or history "they are not making any more". Soil, water, and air are remarkably resilient (buffering) but do have limits beyond which they cannot be utilized without irreversible change.

By appreciation of the soil as a "reactor", one is able to understand what is the capacity and the resilience of a particular soil body. Laws of thermodynamics and kinetic theory allow a better understanding of how the soil functions as the integrator of the environment, that is, the fundamental integrator of the atmospheric, mineralogic, hydrologic and biologic components of the Earth's terrestrial skin. It is by the understanding of these fundamental relationships that human activities (management) can be judged as to their impact on the functioning of the soil, the impacts of human intervention, and the remedial processes that are necessary to maintain the soil as a living entity.

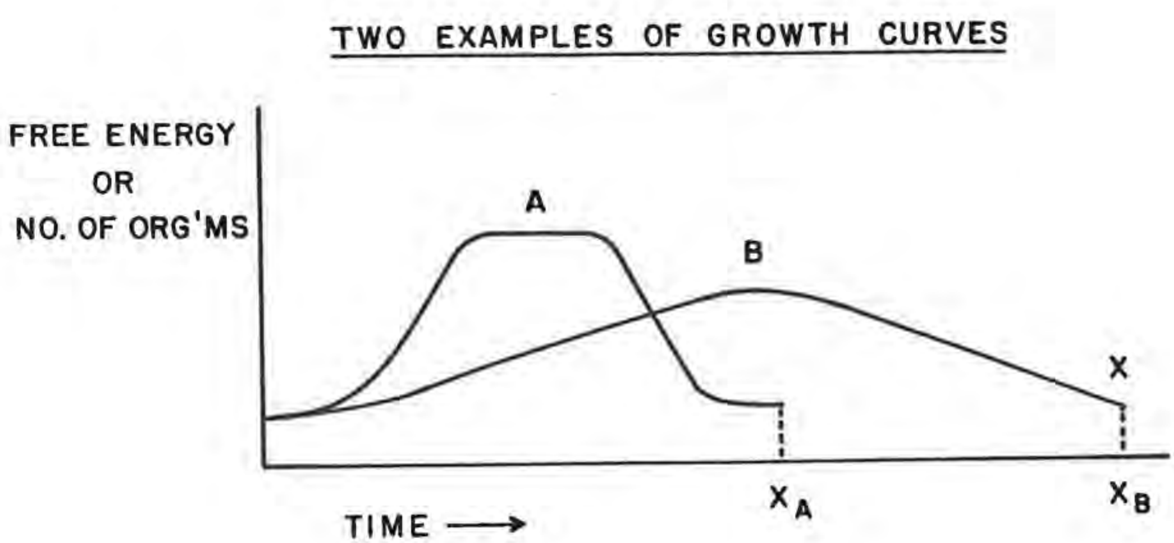

Figure 1.5 Two examples of growth curves proceeding at different rates (area under curves A and B are equal.

1.3.3 As a Geographical Entity

From the previous discussion it is apparent that the soil is a three dimensional entity on the terrestrial portion of the Earth. Too often, authors write and speak about the soil as an individual spot or a two-dimensional object, e.g., the soil profile. In fact, soil is a relatively continuous membrane on the Earth's surface. Within this membrane are things that are considered non-soil such as water, permanent snow or ice, rock and human constructs. As a result of science, and especially reductionist science, humans, not having the capacity to comprehend complex and continuous phenomena, have artificially segmented nature into what they perceive as "homogeneous" categories. This only holds if one can quantitatively and unequivocally define soil from non-soil, or life from death. Nature is a continuum; but in our attempt to understand nature we subdivide this continuum on perceived similarities in morphology, process or function, emphasizing and thereby focusing on similarities and minimizing or ignoring differences. Usually this process is conducted through various levels of generalization, abstraction or comprehensiveness (Cline 1949, 1962). Pedologists have focused much of their attention on the soil profile (two-dimensional) and more recently on the soil pedon (three-dimensional) with a consequent emphasis on soil processes that give rise to vertical differentiation (horizons) of the land surface. Relatively less attention has been given to processes that are related horizontally and spatially across landscapes, be it a depression, hillslope, watershed, or physiographic region. The reality that soil is a geographical (spatial) three-dimensional entity has been largely neglected in research. Many scientists view soil science as a "spot" science. If one accepts that soil is the integrator of the mineral, atmosphere, water and biota, it is obvious that the soil is in fact a spatial volume. The pioneering work of Jenny (1941) and the formulation of the factors of soil formation has been misinterpreted in that Jenny's soil was not a single isolated spot on the Earth's surface. Traditional soil surveys recognize soil as a landscape unit (polypedons) and have developed cartographic concepts to demonstrate this conceptualization (association, catena) yet characterize the soilscape by the modal soil, the profile, and the site (a single isolated spot). There has been a lack of communication among soil scientists, other earth scientists, agricultural scientists, and ecologists in understanding the membrane of soil as having horizontal as well as vertical relationships in components, processes, functions and morphology. This lack of communication and understanding has resulted in numerous debates and pages of scientific literature on soil versus site versus land versus ecotype. The conceptualization is common, the landscape is common, the applied objective may be less common (Rohdenburg 1989). The soil is in fact a landscape; a landscape that may be described and studied at various levels of generalization from a few metres cubed, to hectares, to hundreds of hectares to kilometres squared. It is important in all of these observations and studies that it be recognized that properties, processes and functions form a continuum, sometimes abruptly different but more often changing gradually both vertically and horizontally. The problem still exists as to how we characterize a natural continuum, such as soil.

There is no insurmountable problem if soil is perceived as a single "spot" science, if sufficient spots are examined. With the utilization of geographical positioning systems, geographical information systems and statistical tools such as kriging, spatial relations about the continuum of soil can still be empirically ascertained. This process simply involves rather sophisticated satellite and computer technology.

This approach changes the way in which soil inventories are generated and how soil variability, interpretation and risk assessments are proposed. Rather than the conventional approach of determining soil landscapes as mapping units and determining soil variability (Wilding 1985), a more reliable and statistically more rigorous procedure may be to prepare soil inventories from "spot" sources and then generate "iso-similar" soil landscape polygons. This approach has been utilized in determining forage parameters of quantity and quality by Smith et al. (1991).

A legacy of this historical perception of soil and the fact that most scientific observations about soil have been made by agricultural scientists is that soil is considered by most only as the medium for the growth of agricultural crops and that soil erosion and degradation are important only to agriculture and to agricultural policy. This is unfortunate. Soil erosion and soil degradation as a result of agricultural and forestry practices are important indeed; but the functioning of the soil and its role in integrating the physical environment of air, water, energy and minerals is more vital. It is this integrative nature that allows soil to regulate and buffer the factors that support terrestrial life. Perhaps, keeping in vogue with present times, the term soil should be replaced by a more appealing word such as "ecoterra". The importance of soil as a product of nature would not change but the perception and understanding of its vital role in the environment and the dependence of life on this pervious skin might become more appealing to society. To many, soil is equated to dirt - a negative connotation.

1.3.3.1 Some Examples. If one accepts the soil as a thermodynamic system which follows the predictions of Nature's Laws, then one must accept that soil changes, sometimes slowly, sometimes more rapidly, governed by intrinsic and extrinsic factors. The soil is the integrator of the environment. It is through the soil that the component cycles reach steady states and maintain quasi-stability in terms of capacity and resilience.

As one example, consider the role of soil in the hydrologic cycle. The following table is adapted from Black (1991):

Global Water	Volume	Percent of Total	Residence Time
	m^3		years
Total Fresh	4×10^{16}	-	-
Shallow Ground Water	4.3×10^{15}	11	760
Biosphere	9.7×10^{13}	0.24	17
Soil Moisture	4.1×10^{13}	0.06	4.2
Atmosphere	1.4×10^{13}	0.04	2.4
Rivers	1.2×10^{13}	0.03	2.1

Of the total freshwater (which accounts for 89%), the above table does not include lakes, deep groundwater, and ice and glaciers. One notes that about 0.06% of the Earth's fresh water is held as soil moisture with a residence time only longer than the atmosphere or flowing rivers.

If the infiltration rate and consequent water storage capacity of soil is decreased by 10% as a result of agriculture and forestry practices and human structures such as roads and cities, this is equivalent to 4×10^{12} metres cubed of water that is no longer in the soil and is re-distributed within the hydrologic cycle in such forms as run-off or increased evaporation. This exceeds the amount of water discharging through all rivers in Canada per year (Pearse et al. 1985). Thus, as a result of interruption of Nature's cycles, the capacity of the soil has been altered, the hydrologic cycle perturbed and a new steady state must be established. The effects of this decreased water storage and cycling and new steady state are rate (or time) dependent.

Bohn (1976) estimated that the amount of organic carbon in world soils to a depth of one metre is 3.1×10^{15} tonnes. Again assuming a 10% decrease in organic carbon as a result of anthropogenic activities, this amounts to 3×10^{14} tonnes of carbon that is no longer in the soil "sink" and has found its way into other portions of the carbon cycle. This represents an amount greater than the carbon calculated to come from the burning of fossil fuels in 1980 on a global scale (Hengeveld 1991). This does not consider other effects such as decreased infiltration (loss of structure), water storage capacity, cation exchange capacity, pH, nitrogen, porosity etc., resulting from the loss of organic matter.

The calculated figures presented above are themselves unimportant. What is significant is the process that is being affected and the impact of the process on the ability of soil to re-adjust to new capacity and resilience conditions, and the readjustment of air and water cycles. In addition, the rate at which anthropogenic effects can occur in comparison to the rates by which the soil can re-adjust to these effects may be quite different, and the results and effects on other circulation patterns unknown.

To quote Lucretius once again:

> ". . . whatever increases something else, in its turn replenished . . . earth the universal mother is found at the same time to be the general tomb of things, therefore you see she is lessened and increases and grows again."

Forest floor soils tend to be the most dynamic in terms of rates of change over short periods of time, and the processes during the transformation of organic matter to soil organic matter have been widely examined. The roles of organic matter decomposition and synthesis products have been implicated in numerous pedogenic and ecological investigations. Sanborn and Pawluk (1983) presented some interesting observations in their study of litter decomposition. In comparing the decomposition rate of litter from two species of Populus and one species of Cornus the %C evolved as CO_2 over a 70 day period was higher for

Cornus than Populus and the trends over time were similar. When these authors compared the nutrient content (Ca, Mg and K) of the decomposing litter over a 12 month period the trends were similar for the two genera with respect to Mg and K, however the trends were different for Ca between the two species of Populus. Casual observation showed that in some respects one species of Populus was more similar to Cornus, although the data for the two Populus species appeared to converge towards the end of their experiment. This exemplifies the importance of recognizing that rates and processes which take place during pedogenesis are different and illustrates that process studies rather than only static approaches are needed for better prediction and understanding of the role of organic materials in soil.

In the popular press it is common to stress the effects on the atmosphere of CO_2 resulting from industrialization and the consequent "greenhouse effect". The atmosphere, like soil, behaves as a thermodynamic system. Hengeveld (1991) presents data on atmospheric change. A commonly used diagram showing CO_2 in the atmosphere is presented in Figure 1.6.

If one superimposes a similar trend with respect to land conversion to cropland (Figure 1.7), it is clear that the period following 1900 has had the greatest impact on the amount of carbon in the atmosphere attributed to industrialization. However, it also coincides with the rapid increase in cropland and the concomitant increase in cultivation of soils and increased CO_2 release from soil organic matter. During this same period the area of pasture and grassland remained essentially constant and the area in forests and woodland decreased by over 18%. The question that arises is can the Earth's absorptive capacities of biota, oceans and soil assimilate this combined effect of increased CO_2 from soil organic matter decomposition and industrial activity? The figures also show an exponential tendency of increased CO_2 production and cropland conversion. The questions raised are where is the threshold (the plateau of the growth curve), and can humankind alter the rate at which the plateau will be reached by the adoption of appropriate technology?

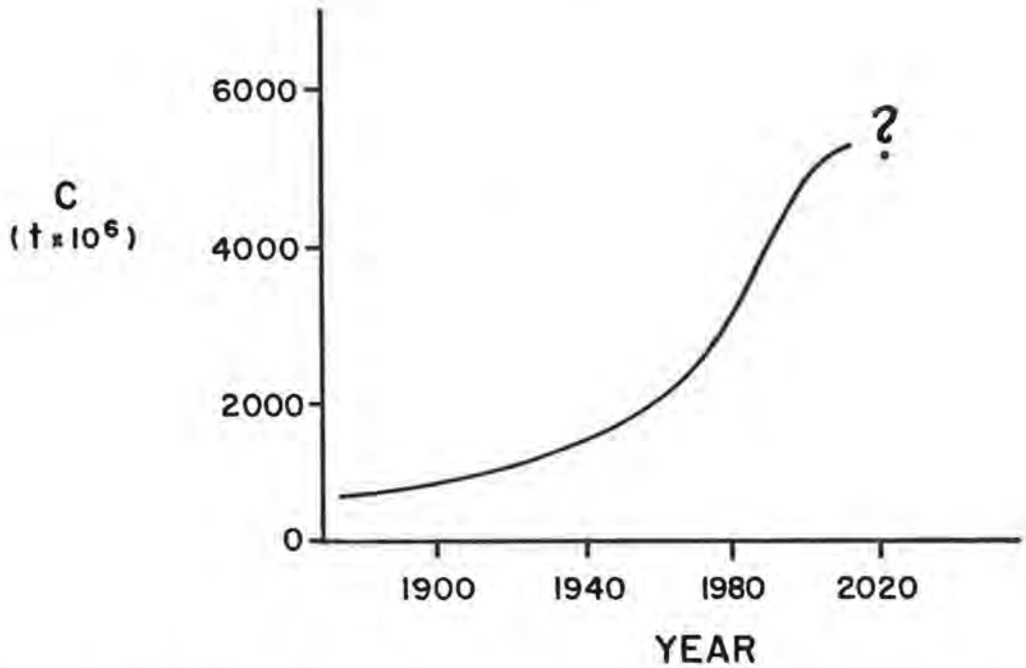

Figure 1.6 Carbon content of global CO_2 emissions from fossil fuel combustion and cement production (adapted from Hengeveld 1991).

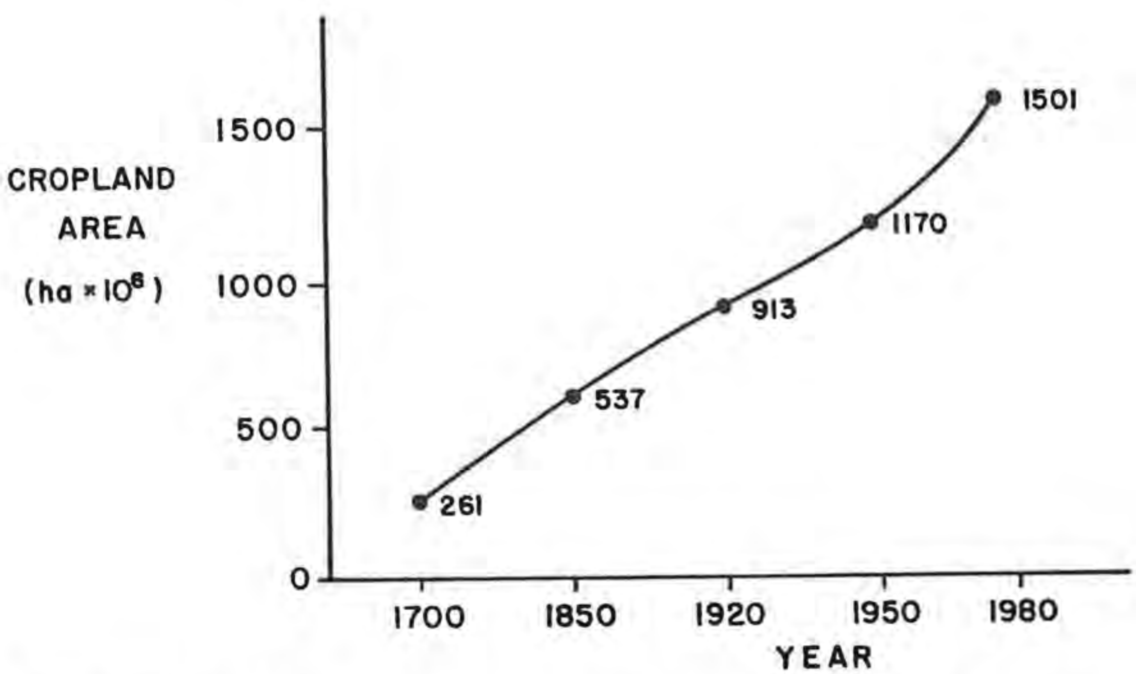

Figure 1.7 Land area of the Earth under cultivation (adapted from Richards 1990).

Other environmental factors also play dominant but poorly understood roles in soil reactions and reaction rates. It is commonly held that reaction rates increase with temperature. Barrows (1992), in examining the effects of temperature on sorption of inorganic ions in soil, argues that in sorption studies evidence about the interaction between time and temperature should be evaluated and stated. He discusses the differences in the direction of temperature effects on the activity of anions and cations, as well as reactions at surfaces. In general, anions shift towards less adsorption with increase in temperature; with cations exhibiting the opposite behaviour. There are however competing reactions that need to be considered.

The usefulness of chronosequences, albeit with the well recognized assumptions, allows the simulation of soil processes over time. Singleton and Lavkulich (1987a, b) presented the following data in their study of the Cox Bay chronosequence on Vancouver Island, British Columbia. Figure 1.8 shows that there is a general relationship of increasing organic matter and extractable Al in a 500 plus year period in the chronosequence. The rate of increase is low for about the first 400 years, then increases exponentially. This illustrates the typical "growth-curve" pattern and the postulation that a certain threshold (activated-complex) must be obtained before reaction rates increase. This is governed by the intrinsic properties of the system, and the rate will be modified by extrinsic factors (the environment). In the above example, a steady state (curve plateau) does not seem to have been reached in 600 years. This emphasizes the significance of an understanding of processes for periods of time longer than most soil investigations address. The soil is dynamic and responds to the Laws of Thermodynamics but only reaction rates (kinetics) will allow prediction of the length of time that is necessary to reach a steady-state and the beginning of the death-phase or decline in the accumulation of organic matter and extractable aluminum. Pedogenesis causes the soil to lose constituents, e.g., soluble ions, and therefore inherent soil fertility and reach a new and different steady state. This loss of plant nutrients is shown in Figure 1.9.

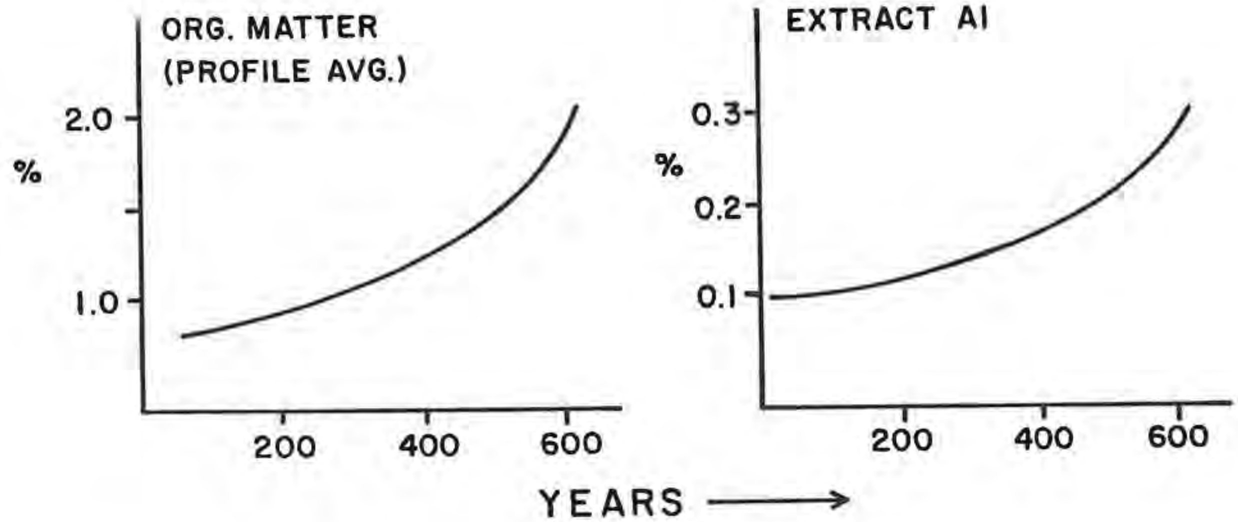

Figure 1.8 The relationship between organic matter accumulation and extractable aluminum (oxalate) over a period of > 600 years.

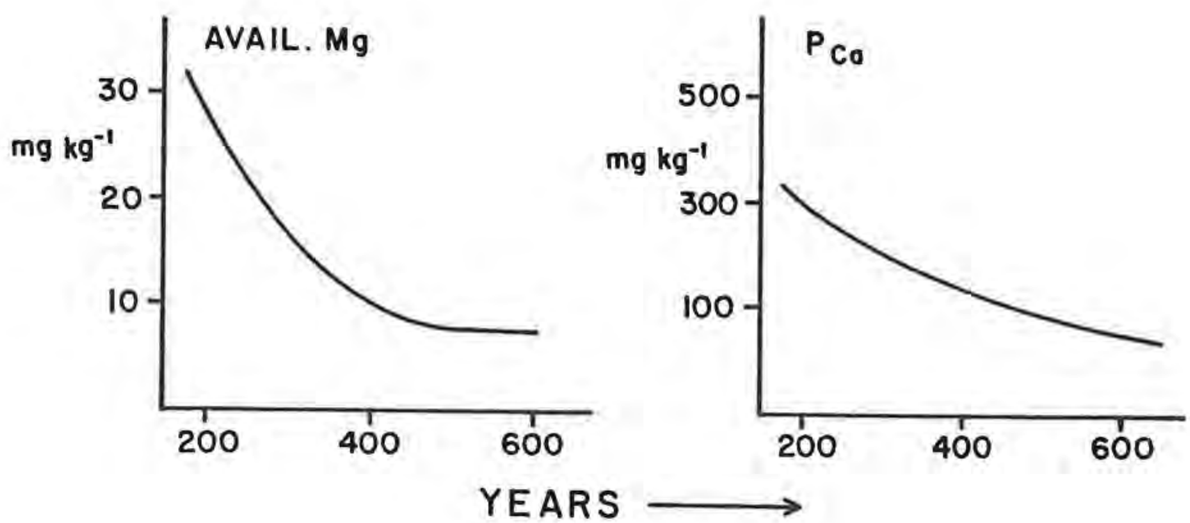

Figure 1.9 Loss of weighted profile average of available Mg and calcium phosphate in a 500 year Cox Bay chronosequence.

Bulk density and soil texture, among other soil factors, play important roles in affecting the relationship of the soil atmosphere as an exchanger of CO_2 and O_2 with the atmosphere above, for a "biologically healthy" soil environment. Richter (1987) provides an interesting treatment of the gas regime in soil. As an example, he shows that the role of a vegetative cover can have a pronounced effect on the CO_2 flux in a soil (Figure 1.10). The example above leads one to speculate how the overall atmospheric cycle is being affected by human activity in managing the vegetative cover of the soil.

The effects of soil management on estimates of soil properties has been studied by several authors (Gregorich and Anderson 1985; Haas et al. 1957; Lavkulich and Rowles 1971; Tiessen et al. 1982). Goldin (1986) showed that with land clearing, pH values increased from about 5 to around 6 following 50 years of cultivation (i.e., one-order of magnitude) as a result of management (liming?). Cultivation resulted in a decrease of 20% organic matter in 35 years with the most rapid decrease occurring in the first 15 years, and steady state did not appear to have been reached. Cultivation over the same period increased bulk density by 26% to 58% on the soils examined and appeared to have reached a steady state in about 25 years. This shows that although soil properties may often be statistically correlated between each other, e.g., organic matter content and bulk density or organic matter and pH, each property is governed by its inherent intrinsic features and its response to the environment.

A commonly held belief is that soil can bioremediate all of society's wastes. Juste and Mench (1992) have shown that the continual application of sewage sludge to soil is not without limit. An example from their work is shown in Figure 1.11.

The data show there is a relationship between sludge application rate and amount of Zn in a crop and in the surface of the sludge amended soil. The data also demonstrate that the soil does not have an infinite bioremedial capacity to offset the continued application of sewage sludge. The soil has an inherent limit.

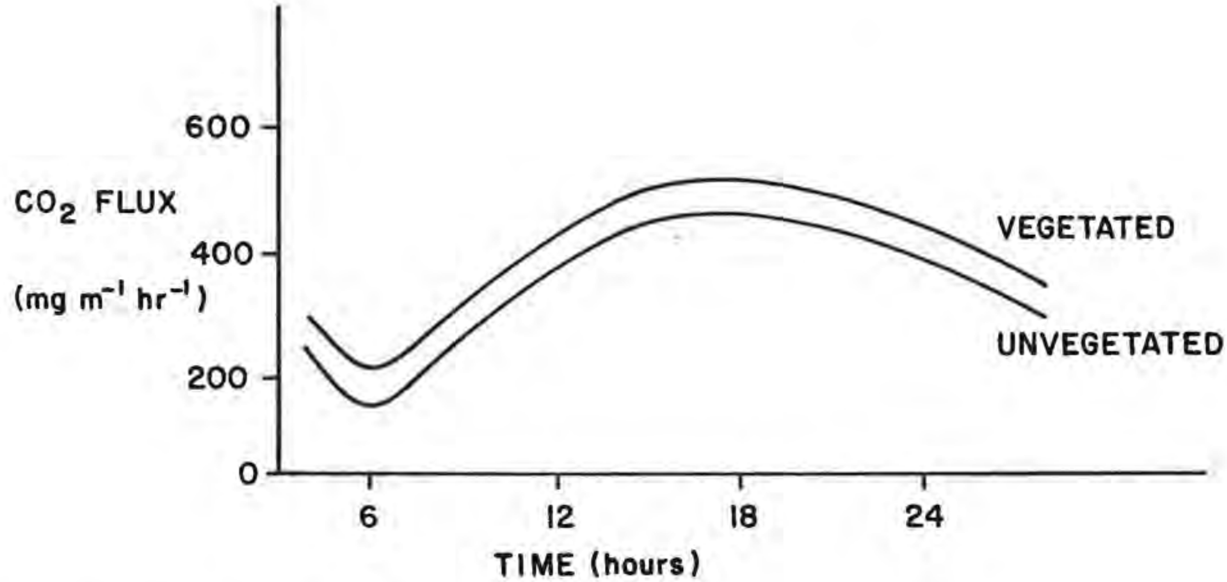

Figure 1.10 Schematic representation of CO_2 flux over a 24 hour period of a sandy soil (adapted from Richter 1987).

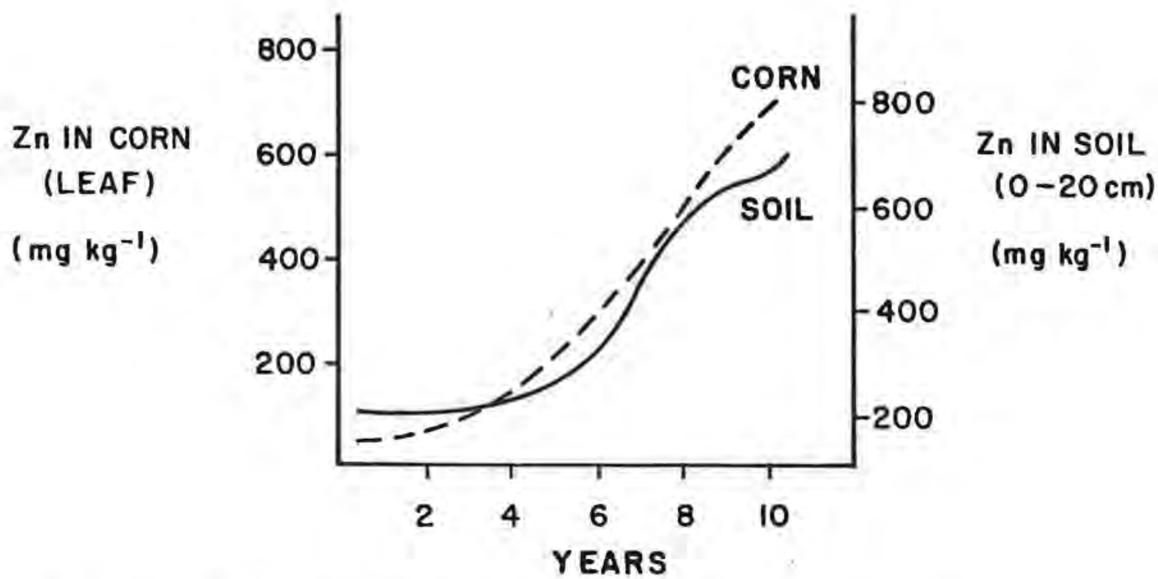

Figure 1.11 Increase in concentration of Zn in 6th leaf of corn and 0 to 20 cm soil from additions of sewage sludge (Bordeaux) at a rate of 100 (dry matter) hectare^{-1} 2 year^{-1} (adapted from Juste and Mench 1992).

The examples given are not meant to be inclusive but merely a representation of the role of soil in the hydrologic, energy and mineral circulation systems of the planet and the implications for biological systems. The examples attempt to illustrate the significance of reductionist approaches, process studies and studies at various scales within the hierarchy of systems in Nature. The attempt is also to draw attention to more holistic approaches to the study of soil as the environmental integrator. The soil is complex, dynamic and not static, a reactor, moderator and an exchanger; it is remarkable, mysterious and fascinating and, most important, essential for life on planet Earth.

Homo sapiens are relative newcomers to the planet. They too are remarkable and mysterious. Humankind has been shaped by its environment and has modified the same environment so that it must now adapt. The Laws of Nature appear to be inviolate even for Homo sapiens. The Earth has an enormous capacity and resilience to the activities of humans; it is however finite.

1.4 The Challenge:

The Earth is a closed system, with the exception of solar energy, the soil is not. The soil exists because of its unique position among the components of the physical environment viz minerals, energy and water. The term "soil" in common usage usually relates to agriculture, other users refer to sediment, land or biosphere when considering non-agricultural aspects of soil. Unfortunately, the concept prevails that soil is merely an admixture of inorganic and organic matter to which management practices such as fertilizers, pesticides, and water can be added for crop production with no effect on the inherent capacity of the soil to function in its significant roles in hydrologic, mineral and atmospheric circulation systems. It is in the holistic sense that life on Earth is dependent on soil. The popular notion that all and any wastes of human activity may be applied to the soil for bioremediation neglects the very truth that the soil is a living system with a finite inherent resilience. The soil is not an equilibrium product, nor a homogeneous body. It is thermodynamically metastable, varies horizontally and vertically and each soil landscape has varying capacities and resilience components that form a continuum on the terrestrial portion of the planet. Soil degradation (erosion, compaction, salinization) only affects immediate biomass production that technology may overcome. More importantly degradation is a strong signal that the balances and cycles of energy, water and atmosphere are being altered and therefore life, itself is ultimately affected. The soil, like air and water, is common property, thus no one is individually responsible, yet everyone is collectively affected.

Soil scientists may be proud of their contributions in agricultural production over the last several decades. More people are better nourished on a decreased land base than ever in the history of humankind. Soil surveys and other natural resource inventories have been most successful in accepting the challenges of the day and have evolved in their utility to resource issues from their original goals to serve agriculture. The demands and utility of soil survey information are varied as is the appropriateness of the present information. Zinck (1990) discusses the vital need for, and yet the recession if not the demise of, soil survey. He discusses soil as a resource limited in time and space and advocates that the three main resource attributes (scarcity, vulnerability and low resilience) beg for more care and that economics deal with soil as a non-renewable resource. He raises a number of questions that are fundamental to soil science. Do we need soil survey? Should soil survey be technology-driven or problem oriented? Can he have a more critical review of basic reasoning and fundamental concepts of structure, hierarchy etc. that support our understanding of soil formation, distribution and potential uses? What about the utility of our basic soil vocabulary such as soil, land, landscape, map unit, entity, etc? To this one may add, are soil scientists addressing the soil as a vital resource, a vital link, an integrator of the environment, in an attempt to understand Nature and the appropriate use and management of this component of Nature for sustained life on Earth?

Wild (1989) raises the question of whether soil scientists are agricultural scientists or earth scientists? As agricultural scientists, Wild argues that our concern has been mainly with plant nutrition, denitrification, nitrate leaching fluctuations in organic matter, acidification and erosion. Are we, as earth scientists, concerned about preserving a healthy environment that can assist archeologists, ecologists, geologists, planners, economists, and sociologists, etc.? Wild suggests that if we are to make a contribution to earth science, we must treat soil as part of the natural environment, and we must, as a consequence, be concerned with global transfers of gases, water and solids between the atmosphere and the soil.

I would argue that it is the responsibility of soil scientists to indeed consider the broader issues. We are trained and educated to understand physical and biological processes and hopefully the interactions between the two. No other area of specialization (discipline?) is better prepared to do so. To do otherwise is shirking a trust and responsibility placed upon us by our colleagues and society. We must also question the basic tenets and practices of our science as we attempt to explain the insights for our science to our colleagues, governments, and the general public. We must learn to communicate better, so that the environmental integrator is given its rightful role in vital decisions made by engineers, economists, sociologists, planners and politicians. Soil scientists must awaken to a new holism. No longer will an informed public allow single answers to complex environmental problems.

Food production merely to feed the under-nourished is no longer acceptable if, by doing so, the atmosphere or the water become no longer life sustaining. Whether existing institutions will rise to the challenge is a moot point. As society begins to understand the essential role of soil as an integral part of life, the challenge will be accepted by natural earth scientists. They may not be called soil scientists, but their challenge will be that of a holistic soil scientist.

The soil is the environmental integrator as it is the Planet's terrestrial reactor and exchanger of minerals, air, water and energy.

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PREFACE

The Environmental Soil Science conference was held August 8-13, 1992 at the University of Alberta, Edmonton, AB. It was sponsored jointly by the Canadian Land Reclamation Association (CLRA) and the Canadian Society of Soil Science (CSSS). The objective of the conference was to share theoretical and applied aspects of soil science. It also served to get participants from the sponsoring groups together to find areas of mutual interest. There were 330 participants from Austria, Bangladesh, Canada, England, France, Germany, India, Japan, New Zealand, Norway, Spain, the Netherlands, and USA.

Abstracts of the oral and poster papers were published in the Canadian Journal of Soil Science (Vol.72, No.3, August 1992. (p.299-353). Volunteer papers covered all aspects of land reclamation, soil science, and public participation in the environmental review process. Seventy six of the 164 volunteer papers were presented as posters.

The invited papers presented in the plenary sessions focused on soil quality and interaction of soils with anthropogenic chemicals, and are published in this proceedings. Publication of the proceedings has taken an unduly long time due to unavoidable circumstances and we apologize for the delay.

Grateful acknowledgement is expressed to our colleagues on the organizing committee (J.A. Robertson, Chair) for their contributions to the success of the conference.

Y.P. Kalra and W.W. Pettapiece, Compilers

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