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THE PHYSICS OF SOIL ENVIRONMENT: PERSPECTIVES AND CHALLENGES IN A CHANGING WORLD

By

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INTRODUCTION

Historical Significance of Soil

Soil is perhaps one of the few substances that have had more meaning for humanity and a long history of interaction with people. This close bond that ancient civilization had with soil was expressed by the writer of Genesis in the following words *"the Lord God formed man from the dust of the earth and the man became a living being"*. The ancients' link of soil with humanity is manifest in the name of the first human, Adam, derived from adama, a hebrew word meaning earth or soil. His existence and livelihood derived from the soil with which he was associated throughout life and to which he is fated to return at the end of his days.

The Babylonian myth of origin is similar to the Biblical. In their creation epic: man was formed from the blood of the god Kingu, mixed with mud from the ground. Other ancient cultures evoke similarly powerful associations. In the teachings of Buddha, the earth and all the forms of life it spawns are spiritually sacred. To the ancient Greeks, the earth was Gaea, the great maternal goddess who, impregnated by her son and consort Uranus (god of the sky) became mother of the Titans and progenitrix of all many gods of the Greek pantheon. Her name is now associated with such modern terms as "geology", "geochemistry", "geography" and even with the name "George" meaning "the tiller of the soil". Among Gaea's descendants was Demeter, the goddess of agriculture and fertility. The Roman equivalents were Tellus, the earth goddess and Ceres, the goddess of agriculture whose name has been metamorphosed into "cereal" an edible grain.

The ancients thus seem to have a better sense of the soil and humanity's connection to soil and maintained a closer intimacy with it than most of us today. Today, our increasing quest to live in soil-less urban settings and our expressions of disdain toward soil, such as "dirt", "soiling", "muddled", "cloddish", that convey negatively humanity's crucial relationship to the soil, betray wholly inappropriate attitude of contempt.

Concepts of Soil

The word soil is derived from the Latin *"solum"* which means "floor" or "ground". Although recognized generally as the common matter underfoot that supports our movement and habitation, soil means different things to different people, depending on their moods, circumstances and to what use soil is subjected. To some like the housewife, soil is a mere dirt or filth, whereas in some parts of southern Nigeria, certain soils are medicinal and claimed to have healing effects when the soil suspension is boiled or "fried" and administered orally to diarrhoea patients. Soil is of interest to Geologists as a product of weathering in relation to their composition of mineral resources. To Civil Engineers, as the material that supports and influences the behavior of earthen structures such as buildings, bridges, pavements and roads, whereas, to the Sanitarian, soil is seen as a sewage and waste disposal medium. With the beginning of agriculture about 10,000 years ago, mankind came to view the soil as the material that nourishes and supports growing plants and thus gives the farmer a practical conception of the soil as a medium in which crops grow.'

THE SOIL, ITS PHYSICS AND STUDY

In general, soil refers to the natural loose material covering the surface of the earth as distinguished from solid rock. It is a body of nature produced by the interactions of the climate, vegetation and surfacial geologic or rock materials through weathering processes. Between one and a half and three unit weights of igneous rock such as granite are estimated to weather to provide one unit weight of soil (Simonson, 1970).On the time-scale of human history, the soil is a non-renewable and destructible resource, requiring thousands of year to form. With an history of evolution or genesis that spans thousands of years, soils are rather ephemeral features on a geologic time scale.

Of particular interest, from agricultural standpoint is the fine earth or "soil" which is the portion of the earth covering with particles less than 2 mm in diameter in contrast to gravels and boulders or stones with particle dimensions in excess of 2mm. The components of the soil, like all other matter in nature, exist in a mixture of the three states of matter, that is, solid, liquid and gas which are referred to as "phases" of the soil (Fig. 1).

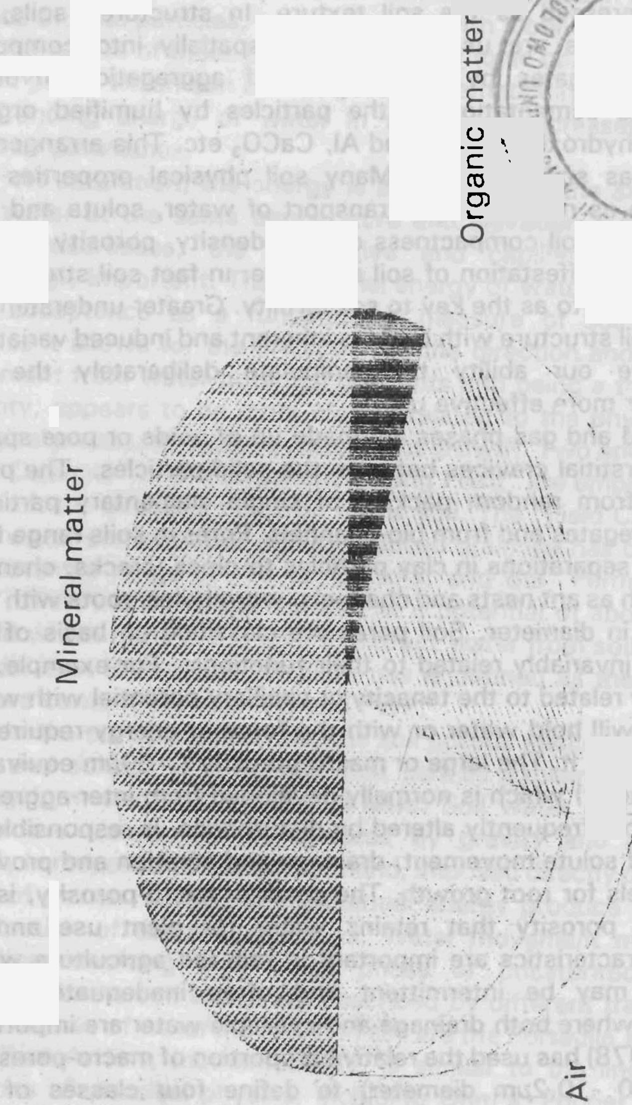

Fig. 1: Main Soil Components

The soil solid phase consists of mineral particles that form the skeletal frame work with which humus or organic fraction is associated. The organic fraction habours a bizarre assortment of soil fauna and flora. The mineral particles are broadly classified primarily on the basis of size into three groups as sand (with diameter of 2mm - 50μm), silt (50-2μm and clay (<2μm). The weight-size distribution of these elementary particles is expressed as the soil texture. In structured soils, the elementary particles are usually arranged spatially into compound particles or aggregates by the process of aggregation involving flocculation and cementation of the particles by humified organic matter, and/or hydroxides of Fe and Al, $CaCO_3$ etc. This arrangement is referred to as soil structure. Many soil physical properties and processes such as retention and transport of water, solute and gas, root penetrability, soil compactness or bulk density, porosity and soil strength are a manifestation of soil structure. In fact soil structure is commonly referred to as the key to soil fertility. Greater understanding of the role of soil structure with both its inherent and induced variations should improve our ability to manipulate deliberately the soil environment for more effective use.

The liquid and gas phases are made up of voids or pore spaces existing as interstitial crevices between the solid particles. The pores may emanate from random packing of single elementary particles, packing of aggregates and from bio-channels. Pores in soils range from 0.003μm plate separations in clay particles to pipes, cracks, channels or biopores such as ant nests and channels, wormholes, roots with tens of centimetres in diameter. Soil pores are classified on basis of size limits which is invariably related to their functions. For example, the size is inversely related to the tenacity or capillary potential with which a pore system will hold water or with the force or energy required to remove water from it. The large or macro-porosity (>50μm equivalent cylindrical diameter) which is normally developed from inter-aggregate pores and is most frequently altered by disturbance, is responsible for rapid water and solute movement, drainage and aeration and provides existing channels for root growth. The small or micro-porosity, is the intra-aggregate porosity that retains water for plant use and its associated characteristics are important in rain-fed agriculture where water supply may be intermittent and often inadequate. Under circumstances where both drainage and available water are important, Thomasson (1978) has used the relative proportion of macro-pores and meso-pores (60 - 0.2μm diameter) to define four classes of soil structure. The best class has a macro-porosity of >15% and meso-

porosity of <35%. The worst class has a macro-porosity of <15% and a meso-porosity of <35%.

By soil's porous nature, it plays a dual role in that it constitutes a mobile reserve for water and nutrients or solutes dissolved in it which must bridge the gap between plant requirements, which are practically incessant, and the supply of water, which is intermittent and may be infrequent and inadequate. The soil water is localized in films and in the surface of solid particles, which retain it with a bonding energy varying with the nature of these particles and their ionic composition. It is also held in pores which can be compared schematically to capillary tubes. The bonding energy of water in the pores increases as the pore diameter diminishes.

At saturation, the energy is approximately the same as that of pure water at the same temperature and elevation but as soil water content decreases, the adsorptive and capillary forces become increasingly important. The potential energy of water in soil has gained wide acceptance as a fundamental measure of soil water status because it allows for the prediction of the direction and rate of water movement from water potential gradients and being a thermodynamic quantity, appears to be more closely related to the physiological and biological processes which control plant growth. Two energy levels the "Field Capacity" and "Permanent Wilting Point" are empirically defined to delimit the available reservoir in the soil. The "Field Capacity" (FC), is the water content after gravity-induced drainage has ceased usually at a potential range of -10 to -33 kPa, and the "Permanent Wilting Point", (PWP) is the water content at a potential of about -1500 kPa beyond which roots are unable to extract water from soil. The amount of water that is available for plant use is defined as the difference in moisture content between FC and PWP.

In the transportation role, the soil porous medium interacts with water and solutes in a manner that can be explained and deduced starting from elementary physical laws. Soil water and its dissolved solutes are transported downwards by gravity and upwards and laterally in response to climatic demand, imposed directly or through the action of plants. Variations in potential energy produce movement in the direction of decreasing values. Water movement may be under saturation involving only liquid phase or unsaturation (diphasic) conditions in the soil which are described by different transport laws. The basic laws of water movment in soil are the Poiseulle's and Darcy's laws. Darcy's law, mathematically, is similar to the linear transport equations of classical physics, including Ohm's, Fourier's and Fick's laws. The essential phenomena involved are infiltration (the process of water entry into soil), redistribution, drying or evaporation and capillary rise.

The larger pore spaces, constituting the gaseous phase or soil atmosphere are filled with gases (composed mainly nitrogen, oxygen and carbon dioxide) in a direct reciprocal relationship with that of water. The two dominant processes involving oxygen consumption and carbon dioxide production on the one hand and gaseous exchange with surroundings on the other characterize the redox properties of soil which influence other soil properties and microbial metabolism. Apart from convective flow, the air components are exchanged by means of diffusion. In a well aerated soil, the gas phase contains 18 to 20.5% O_2, but this can drop to 10% after rain or even as low as 2% around roots and poorly structured zones. CO_2 is higher than in the open air (0.03%) and on the average is in the range of 0.3% to 3%. Nitrogen concentration is very close to its free atmospheric level of about 78%. Various other gases can be found in the soil such as N_2O, argon, H_2S methane etc (the latter three under strong anaerobic conditions.)

The soil is thus a dynamic open ecological system with a complex milieu of competing and cooperating physical and biological reactions that determine its productive use. From agricultural standpoint, soil productivity can be viewed as integrating those attributes of the environment which determine the availability of water, air and nutrients to plant roots in the absence of toxic substances and physical impediments in the soil medium. In order to manage the soil system so as to maximize water and nutrient use efficiency, the qualitative understanding of how the physical regime operates as well as a quantitative knowledge of its mechanisms and the rates of its governing processes are essential.

The attempt to understand what constitutes the soil and how it operates within the overall biosphere which is the essential task of soil science, derives from both the fundamental curiosity of a man as well as from growing necessity to manage the finite resource for sustainable use as a medium for crop production.

ISSUES OF SOIL-RELATED PROBLEMS

Efforts to use soil in ways for which they are unsuited or poorly suited have led to painful failures of many developmental projects, reduction in soil productivity and utility of which declining crop production and depressed socio-economic pattern of the people are a reflection. The historical human-soil interaction dating back to 7000

years (McCraken, 1987) has not been entirely positive. Wide-spread evidence of abuse, mismanagement and neglect of soils is believed to be the reason why several ancient civilizations failed and went into extinction, notably the Mayan civilization in Central America (1000 years ago), the Harappan civilization (1700 B.C.) in the Rajasthan desert of northwest India and many others in the Middle and Near-east and North Africa. Man-made threats to soil are associated with land use for food production and for other activities that generally impact the total environment.

Food Production

Soil is at the centre of the most pressing problems facing mankind today, that is, food, economic and ecological problems. According to the United Nations medium projects, world population could reach a stationary level of some 10.5 billion by the year 2110 compared with the 5 billion at present. The implication of this is that by the time the world is reaching close to population stability, demand for food and agricultural products could be more than three times its present level (FAO 1981), with serious pressure and potential confrontations with the soil. Although large food surpluses have been produced in Europe and North America in recent years due largely to scientific and technical improvements in agriculture, problems of food are as great as ever and real hunger continues to exist in much of the developing world. While world agricultural and food production per capita increased some 10% over 2 decades, in Africa they fell by about 15% and food sufficiency declined to under 90%. Aggregate grain production in Nigeria in 1991 was 13.8 million tons with a per capita production of a miserably low 160 kg. (Nigeria, Ministry of Agriculture quoted by *Newsweek*, Aug 1992). Serious soil related problems of acidity, salinity, nutrient and water stresses and risk of erosion are widespread, and undermine the conditions that can make green revolution a reality.

There is also increasing concern about the effects of agriculture on the environment. The phenomenal increases in food production associated with the quantum leap in agricultural technology known as the "Green Revolution" was attained along with the development of new high-yielding cereal hybrids, by the massive application of fertilizers and herbicides often in association with irrigation water. The negative effects of green revolution in terms of soil and groundwater pollution are beginning to emerge and cause concern especially in developed countries. There is special concern, for instance, that nitrates and pesticides applied to the soil may be polluting water and food that they are harmful to the health of animals and humans. In the case of nitrates, there is concern that they are causing eutrophication in the sea and inland waters and that they may be inducing the formation of "greenhouse" gases. So great are these concerns that they are prompting several rich nations to introduce legislation to control the use of chemicals in agriculture. In certain other nations, the response has been the emphasis on low-input agriculture based on sound ecological principles such as chemical-free organic farming.

Possibly, the best known threat to soil quality is erosion that removes topsoil and leaves behind a soil which generally supports poorer plant growth. In the humid and sub-humid areas, water erosion is all too common and can be catastrophic. The evidence of severe soil degradation is highly visible from the wide-spread occurrence of devastating gullies. Less visible but no less real, is the sheet-erosional depletion of soil productivity resulting from soil physical degradation, loss of topsoil, nutrients and organic matter. Soil degradation as a result of erosion is induced mostly by large-scale forest clearing for food production and by overgrazing. Unwanted contaminants unsafe to humans may also be added to soils in animal manures or fertilizers.

The Environment

Difficulties in landscape development are encountered where the nature of soils is unknown or poorly known prior to their use. Examples include troubles with house foundations and basements, highway and bridge construction, functioning of waste disposal sites and housing development. The failures of road and house foundations and cracking of basement walls are known to occur in specific soils (Vertisols) which have the capacity to shrink and swell with changing moisture content. Soils formed in colluvium derived from shale and sandstone are known to be usually prone to slides and become unstable when used as sub-grades in highway construction. Corrosivity of uncoated steel pipes and concrete buried in soils is generally higher in wet soils with fine textures and high salt contents than in well-drained coarser textured soils. Septic tank effluent disposal is generally not a problem on well drained soils and if dwelling and effluent disposal systems are not closely spaced. In most communities, human wastes are disposed off in dung-hills or pit-latrines or in soak-away pit systems. Ogedengbe (1980) reported for a rural setting in Ife that such pit-latrines could and did actually contaminate the water of co-existing wells and attributed observed incidence of high water-borne diseases such as cholera, typhoid fever,

infectious hepatitis and gastro-enteritis to the possibility of such contamination and the extent of which as reported by Ogedengbe and Aina (1983), depends on the physical properties of soil separating the two systems.

Soil is a receptacle to atmospheric fall-out of emissions from industrial activities which constitute one of the major sources of environmental pollution. For example, in cement industries, much dust is released into the atmosphere with both visible and latent consequences on soil, vegetation and human health. The deleterious effects of cement which is a mixture of Calcium disilicate, tricalcium silicate, tricalcium aluminate, and tetracalcium aluminoferrite on humans and vegetation is attributed in part to the enrichment of the constituent elements in cement-contaminated soils, soil being a port of entry into the food chain. Asubiojo et al (1991) reported substantial enrichment of Ca, Mg, S, Fe, Ni, Cu, Zn, Pb and Cd in soils in the neighbourhood of two cement factories in Nigeria.

Soil itself can be a pollutant; wind-blown dust is a pervasive air pollution as eroded sediment and associated chemical load are in waters. Wide publicity has been given to predictions that the temperature of the earth's surface will increase due in part to increasing release of CO_2 which has influence on radiation received by and reflected from the earth, i.e the "greenhouse effect". Prentice and Funk (1990) have predicted an increase of 5.4°C in average temperature and 17.5 mm day^{-1} in precipitation from doubling the atmospheric CO_2 levels. Other gases which may affect change in temperature include methane (CH_4), nitrous oxide (N_2O), ozone O_3 and chlorofluorocarbons (CFCs). More recently, we have been made aware of the depletion of ozone over the Antarctic with which chlorofluorocarbons CFCs are implicated. Soil processes are involved in the transfer of most of these greenhouse gases between the terrestrial ecosystems and the atmosphere. In addition, soils are the primary source of radon (Rn) gas which may concentrate in closed dwellings to become a health hazard (Nazaroff and Teichman, 1990). Although most of the recent increase in the atmospheric carbon dioxide is attributed to fossil combustion, much also comes from tropical deforestation (Detwiller and Hall, 1988) and other soil management practices, such as plowing and draining wetlands. Natural wetlands and rice paddy soils are major sources of atmospheric methane. Major sources of nitrous oxide are less known but may be associated with various nitrogen transformations in soils.

Soil acidity, an old problem in humid regions is aggravated by deposition of emitted acid-forming oxides of S and N downwind of some industrial areas (acid rain) due to burning of fossil fuels. Detrimental effects of soil acidity have been known for many years (Truog, 1938). They include inhibition of important microbial processes, reduced availability of essential plant nutrients, and increased solubility of Al, possibly to toxic levels in the soil and depressed food production capability.

There is increasing evidence of soil's infinite capacity to dispose of harmful pollutants from agricultural and industrial activities and the possibility of its capacity over-taxed or abused due to inadequate knowledge of soil. The early complacency and uncritical use regarding the soil as an -all-powerful "filter" capable of detaining and recycling all manner of wastes applied to it - has given way to a realization that the soil can become a mere way-station, allowing some toxic materials to migrate beyond where they can be treated effectively. Although the problem lies in the interdisciplinary realm including such related fields as soil chemistry and microbiology, soil physics has made contributions in defining the physical transport phenomena invariably involved in the pollution and disposal of pollutants by soil.

CONCEPT AND GOALS OF SOIL PHYSICS

Soil physics is the sub-discipline of soil science that deals with the physics of the soil environment, aimed at a better understanding of the soil-plant-atmosphere interactions and proper management of soil to enhance food production. How much of soil is occupied by the different component phases, how the phases are interrelated, how air and water get into the soil, how they are circulated and stored, the laws that are operative in the movement of air, water and solute in the soil are all of interest from the pure soil physics standpoint. Soil Physics rests upon the theoretical basis furnished by the principles and methods of physics and mathematics to explore such physical properties and processes including texture, soil structural development and dynamics, water and solute retention and transportation, permeability to water and air, water and air diffusivity, sorptivity, infiltration, evaporation, soil temperature etc. Significant advances have been made also in the understanding of groundwater contamination, uptake of water and nutrients by plant roots, crop water requirements and water use efficiency, erosion and run-off, tillage mechanics, and soil-tillage interaction, modelling of major factors controlling movement of nutrients and pesticides, transport of surface water and ground water. Contemporary soil physics has tended to be associated with the modelling of the soil system to enhance observations and predictions

of certain quantitative aspects of the behavior of the real system.

SCOPE OF RESEARCH AND CONTRIBUTIONS TO KNOWLEDGE

Mr. Vice Chancellor, distinguished ladies and gentlemen, the scenario of my humble contributions to the knowledge and management of the Physics of Soil environment is considered a sensitivity test as well as a progress report. Noting the paucity of "hard" information on the Physics of Soils of the tropical humid and sub-humid ecosystems and consequent constraint on the realization of sustainable agricultural use of the soils, my adventure started with the characterization of the physical regimes of diverse soils constituting the agricultural base of these regions, followed by the elucidation of soil behavioural changes associated with use and finally, the development of management systems for sustainable use of the soils.

The dominant soils, occupying over 80% of the land area, are adjudged very fragile, that is, they are characterized by properties that are easily degraded upon use. They are characterized by coarse-textured surface soil horizons with low contents of clay that is of low activity and low organic matter contents. More than 60% of the soils contain less than 20% clay and less than 2% organic matter (Aina and Periaswamy, 1985). Although the bulk density of the surface soils is favourably low (generally below 1.20g/cc), some of the soils have pronounced gravel horizon or stone line at shallow depths, often as thick as 60cm, which according to Aina and Fapohunda (1986) could constitute a rigid matrix that can be restrictive to water movement, root penetrability and plant water uptake in the soil profile (Fig. 2). Available water holding capacity of the root zone, that is the maximum amount of water available to plants the soil can store, is in general undesirably low, which according to Aina and Periaswamy (1985) ranges between 2 cm and 5 cm within the root zone. The soil moisture retention pattern is such that most of the available water is released at low suctions of between 0.03 and 0.05 MPa. The proportion of water-stable aggregation (mostly >0.5 mm in diameter) is high (as much as 90%). The soils are also highly permeable; it is not uncommon for soils to sorp 400 cm of water in 3 hours. Relationships between soil physical parameters useful in agronomic planning were quickly developed from the massive research data that emanated from the initial characterization of the physical regimes including those between FC, PWP, AVWC, texture and bulk density (Aina and Periaswamy (1985), soil structure and organic matter content, soil structure and infiltration, hydraulic conductivity, bulk density, soil strength and tilth. Aina (1989),

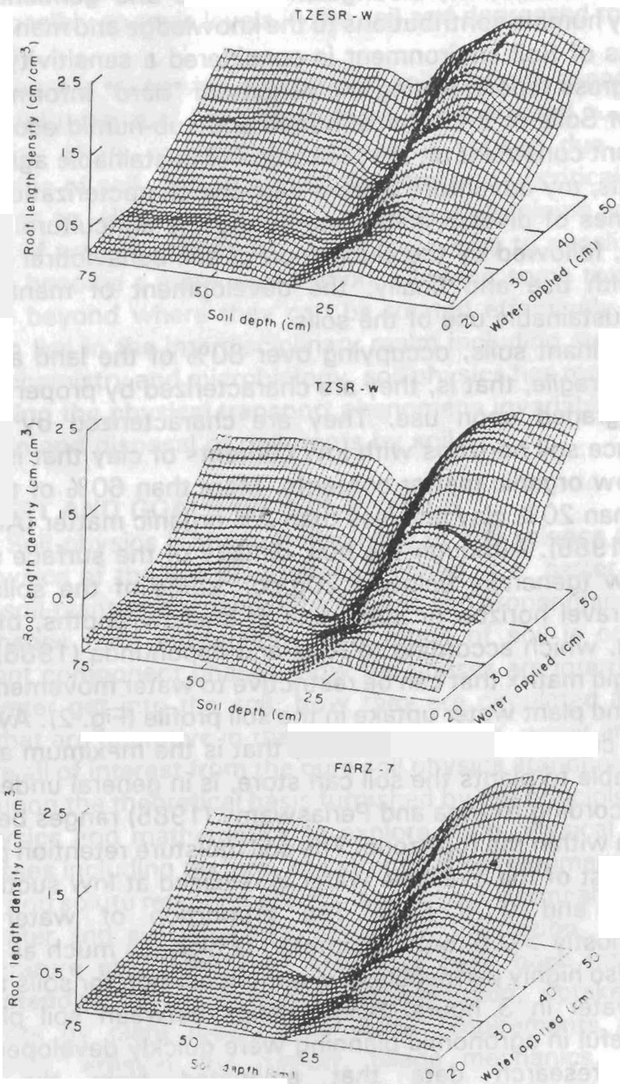

Fig. 2: Average Root Length Density (RLD) as a Function of Soil Depth and Irrigation Level (Aina and Fapohunda, 1986)

Aina, Lal and Taylor (1979) attributed soil aggregate stabilization mostly to organic matter and to, lesser extent the hydroxides of Fe and Al in soils exhibiting high to intermediate contents of free Fe and Al oxides. The moisture retention/release characteristics are due to low content and the low activity of the clay fraction and high sand content. Aina (1982) also related soil dispersibility, plasticity and aggregation of Ngala soils (problem) from Northeast Nigeria to the extent and species of saturation cations.

Removal of soil from forest by land clearing and subsequent use especially cultivation results invariably in immediate and drastic changes in soil physical properties. First and foremost, it bares the soil to the effects of climatic elements which affect soil microclimate and other properties, including seed germination and subsequent plant development, soil fauna and uptake of water and nutrients by plant roots. Forest clearing has been reported to increase by 25-folds incident radiation reaching the soil surface from an average of 10 g-cal/cm^2 per day. Aina (1981, 1982) has reported surface soil temperature differences as high as 10°C between soil under forest and bare conditions. Impact of the forest conversion on soil depends on the method of clearing. Mechanical clearing results in greater soil compaction and decline in favorable structural attributes such as the proportion of macropores and infiltration rate than traditional or manual clearing methods. For a range of land-clearing methods tested on Alfisols, the order of degradative change in soil physical properties was manual clearing < tree pusher < shear blade < tree pusher/root rake. Post-clearing and subsequent uses produce more significant changes in soil physical regime. In a comparative study of soils under long-term forest fallow and arable cultivation at Ife, Aina (1979) observed that organic matter content decreased by four folds after five years of cultivation, bulk density increased from 1.2 to 1.5 Mg m^{-3} and as much as 80% of the initial aggregation under forest was destroyed. Stability of soil aggregates was reduced by 80%, saturated hydraulic conductivity by eight-folds (Fig. 3); Reductions in total porosity from 58% to 38% and in transmission porosity from 35% to 10% were also observed.

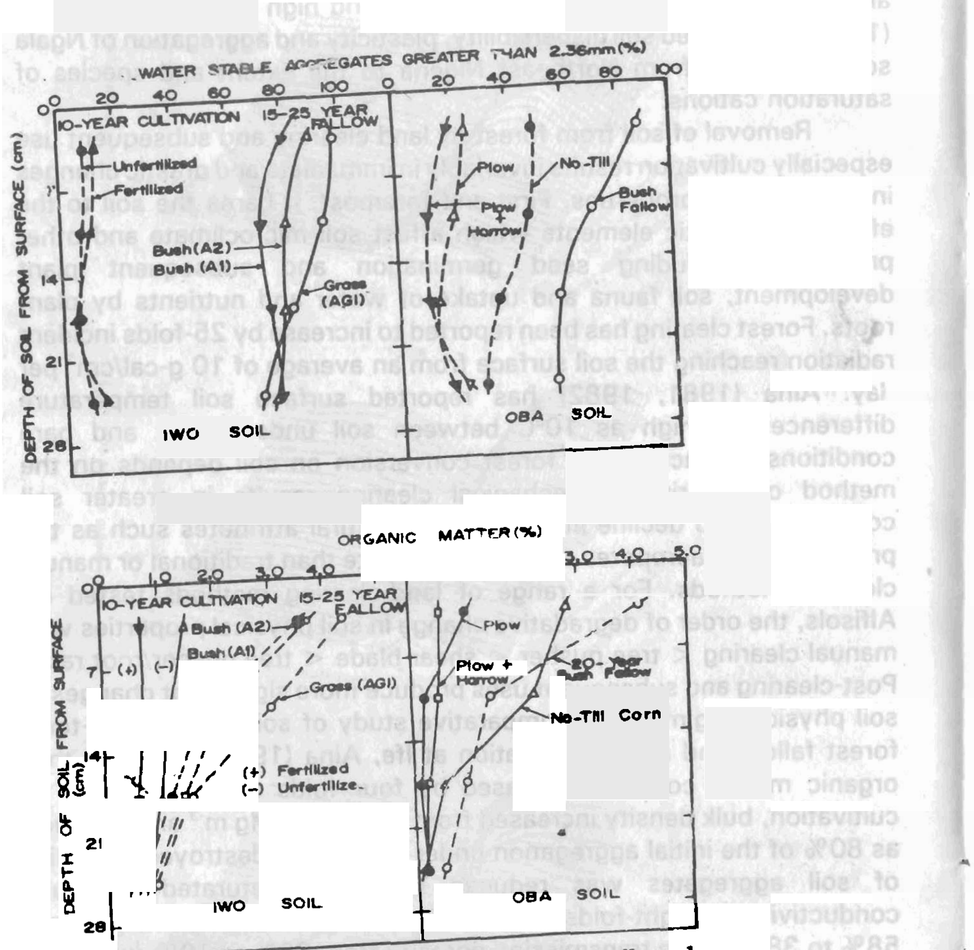

Fig. 2—Organic matter contents of Iwo and Oba soils under fallow and continuous cultivation.

Fig. 3: Distribution of Water Stable Aggregates (above) and Organic Matter with Soil Depth in Two Soils Under Bush Fallow and Continuous Cultivation (Aina, 1979)

Wilkinson and Aina (1976) reported 50% reduction in the infiltration capacity from an average of 115 cm hr^{-1} under forest after one year of cultivation. This soil behaviour under cultivation was attributed to the rapid decline in structural attributes caused by loss of organic matter and cultivation. Apart from compaction from vehicular traffic, decline in soil infiltration rate and macro-porosity following cultivation is also partly *due to reduction in the activity of soil fauna (especially earthworms)*. The burrowing activities of earthworms are known to create large pores that could enhance soil macro-porosity and movement of water in soils. Aina (1984) reported an 8-fold reduction in earthworm activity due to forest removal and 19-fold reduction in the amount of bio-channels with a minimum infiltrability of 0.9 lit hr^{-1}. He reported that infiltration rate of soil under forest declined from 60 litres/hr to when earthworm activity was eliminated (Fig. 4).

Tillage for seed-bed preparation, weed control, incorporation of organic materials into soil and other purposes is perhaps the most ubiquitous of cultivation practices. In general there are usually several *tillage alternatives broadly classified as mechanical or plow-based tillage* (conventional), reduced and no-tillage or conservation tillage. The suitability of a tillage system which is judged by its effectiveness in soil and water conservation and high crop yields, depends on a number of factors including soil characteristics, nature of crop to be grown, agro-ecological and climatic environments and even time of the day for plowing. The London "TIMES" of 14 October, 1992, reported that studies in Germany, Denmark, Britain and the US have shown that plowing in the dark can reduce amount of weeds, by as much as half, and increase crop yield than plowing by day due to the fact that many weeds produce dormant seeds that can survive for as long as 50 yrs or more in soil but require light, even a flash of it lasting a fraction of a second such as during plowing to germinate.

Traditional tillage, done mostly by manual labour, and simple native hand tools (hoes) *is used to heap surface soils into hillocks or mounds* or ridges on which a range of crops are simultaneously grown as

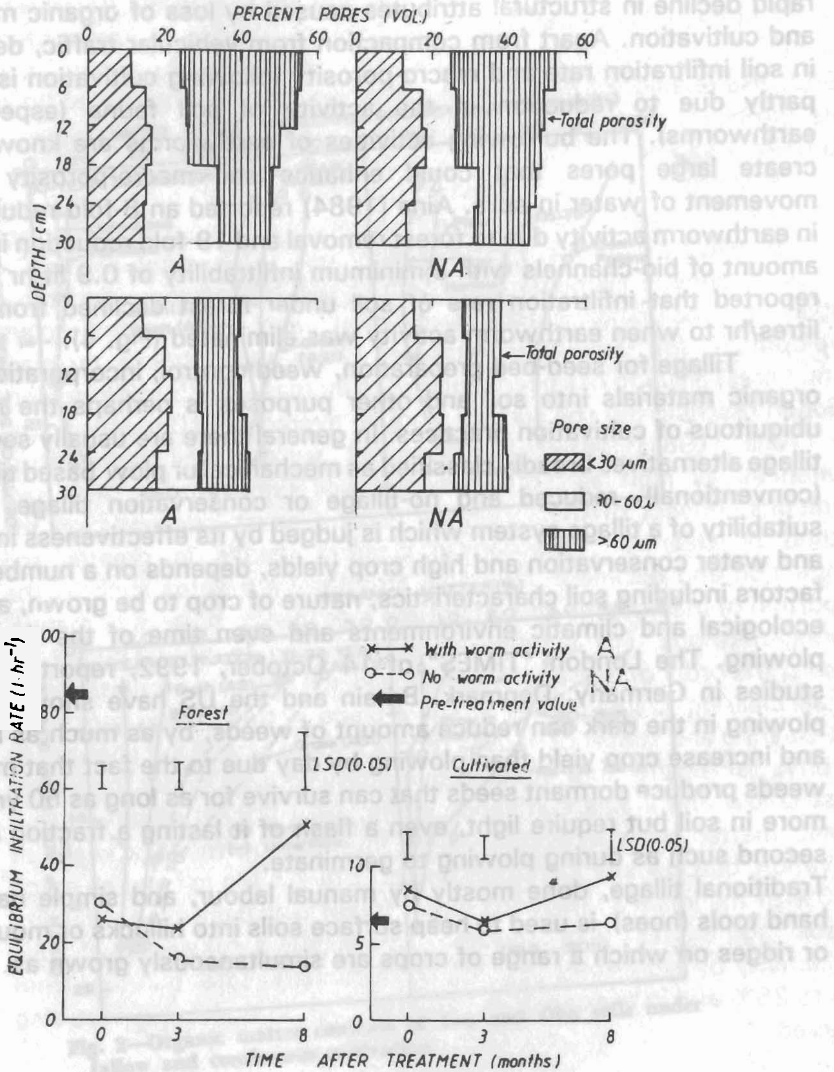

Fig. 4: Pore Size Distribution (above) and Infiltration Rates (below) of Soils Under Forest and Cultivation as Influenced by Earthworm Activities (Aina, 1984)

intercrops. A number of comparative tillage studies conducted here have considered the traditional system to be relatively efficient in terms of soil and water conservation and adaptable to subsistence, low-input and labour-intensive agricultural system but a poor weed-control method compared to the plow-based or conventional method. One of the most significant developments in recent years is the growing use of heavy tractors and machinery to plow land more deeply and rapidly and to carry out such operations as planting, spraying and harvesting with increasing efficiency in an effort to increase agricultural production. The blessings of mechanization, however are not without certain attendant dangers. Even though tillage would beneficially loosen root-restricting or naturally compact soils to minimise soil strength and impedance and increase soil permeability to water (Cassel and Nelson, 1985; Cassel, 1982), and adaptable to crops crops with tuberous underground parts such as cassava, soils with low organic matter contents and unstable aggregates are particularly vulnerable to tillage-induced soil degradation. Tillage and associated traffic can cause deformation of soil structure through shearing, compressive and tensile stresses which is manifested in soil compaction, diminished pore continuity (Ball, 1981; Goss et al, 1984), disruption of faunal (earthworms) burrows and enhanced mineralization and rapid loss of organic stabilizing materials. Equally insidious is the tendency to pulverize the soil excessively with the consequence of making it extremely susceptible to erosion by wind and water. The soil water content is an important parameter in determining the influence of tillage on soil structure. According to Aina (1985) soils are most friable when tillage is carried out at moisture contents at or below the lower plastic limit whereas at higher moisture contents, soil is easily deformed and leads to compaction. Soil compaction is a form of mechanical pollution which may be due to soil setting as a result of cultivation-induced loss of soil organic matter and structural stability or due to compaction from motorized farm and tillage operations. Compaction of agricultural soils is known to detrimentally influence root penetration and crop yield. Root growth is severely impeded by soil bulk density values (Mg m^{-3}) that exceed "rule of thumb" magnitudes of 1.55 on clay loams, 1.65 on silt loams, 1.80 on fine sandy loams and 1.85 on loamy fine sands (Bowen, 1981). A number of studies have reported reductions in crop yields as a result of soil compaction. In a greenhouse investigation simulating cultivation-induced effects of compaction on maize, Aina (1980) observed that compacting an Alfisol from a bulk density of 1.2 to that of 1.6 Mg m^{-3} reduced shoot and root weights by 54% and 65%, respectively and depressed nutrient (K) uptake at optimum soil mosture (Fig. 5). Mechanical impedance is probably the most ubiquitous of physical constraints to the unhindered emergence of germinating seedlings and growth of crop roots through soil. Seedling emergence is influenced by crop type and soil strength which is a function of soil compaction and moisture suction. A soil penetrometer resistance value of 2 MPa is generally considered to severely restrict root growth (Glinski and Lipiec, 1990). Aina *et al* (1985) investigated the effects of 4 levels of soil compaction and 5 levels of moisture suction on the relationship between penetrometer soil strength and seedling emergence of maize and cowpea. We observed that cowpea ceased to emerge when soil strength exceeded 8 kg cm^{-2} in clay loam soils and 10kg cm^{-2} in sandy clay loam and sandy loam soils. Corresponding values were 14 and 18 kg cm^{-2} for maize. Additionally, many soil types contain indurated horizons in the soil profile such as gravel or stone layers which are naturally resistant to root penetration. Aina and Fapohunda (1984) reported that incidence of such compact layers at about 22-cm depth in an Alfisol significantly reduced the amount of roots that penetrated the layer by 30%, root length density and root length/weight ratio, water extraction by roots and water uptake per cm of root (see Fig 2).

Minimizing tillage may diminish many of its detrimental features. The zero-tillage with crop residue mulch, is a system in which crops are established without seedbed preparation and chemicals are used to suppress weeds. The beneficial effects of the zero-tillage system according to long-term studies by Aina, Lal and Taylor (1977) and Aina (1982) are associated with the provision of surface protective mulch, reducing erosion, maintaining soil organic matter at high levels and favorable soil temperature regimes, improving soil moisture retention capacity and nutrient use efficiency and higher sustainable crop yields where the system is found suitable. No-tillage has been found to reduce erosion to insignificant amounts even on slopes as steep as 15% compared to soil loss as high as 68 tons/ha under conventional tillage system. These beneficial effects of zero-tillage are however limited by certain bio-physical and socio-economic conditions. Zero-tillage was found to be less desirable on poorly-drained and hydromorphic soils and for crops with tuberous underground parts such as cassava (Manihot esculenta) and yams (Dioscorea spp) which require conventional seedbed for normal development and ease of harvesting (Aina et al, 1979b, 1982). For example, Aina (1982) reported about 40% reduction in cassava yield under zero-tillage compared to the conventional tillage. In Nigeria, as in most developing countries today,

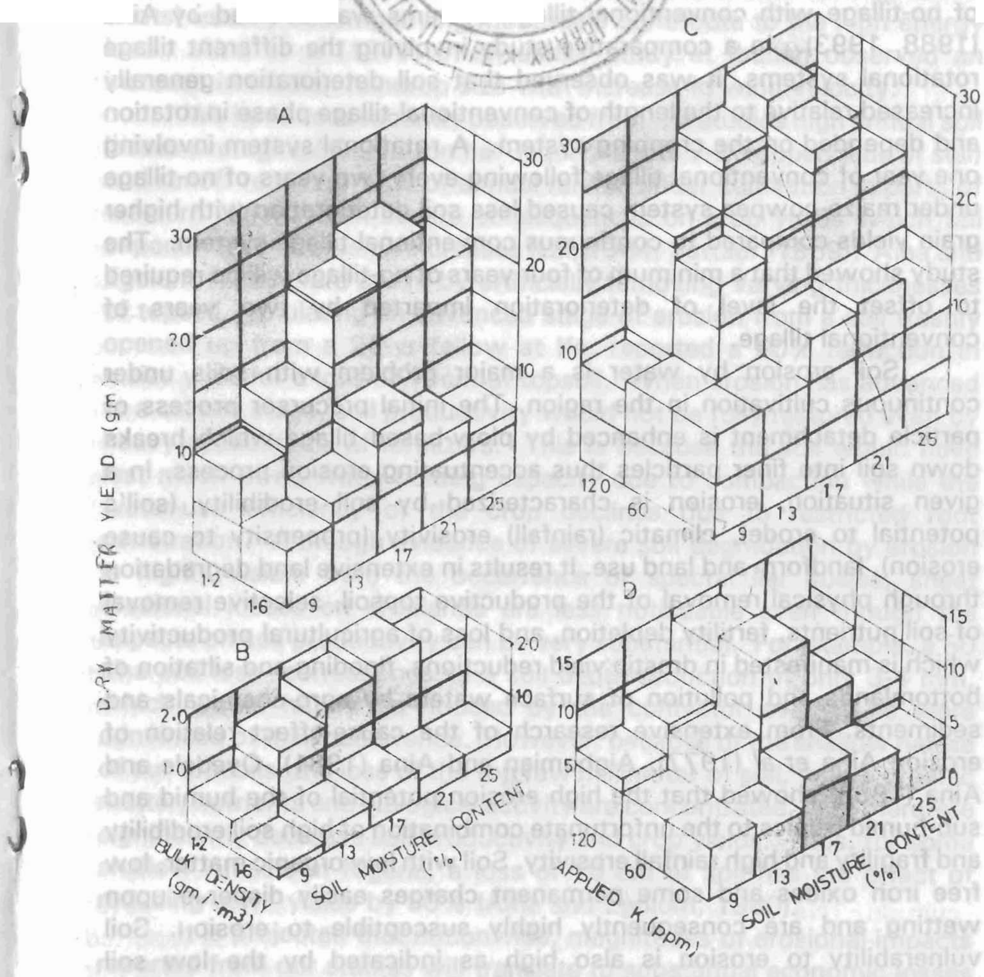

Fig. 5: Effects of Soil Compaction, Potassium Fertilization and Moisture Regime on Dry Matter Production of (A) Shoot and (B) Roots of Maize (Aina, 1980)

herbicides when not adultrated, are increasingly unavailable or prohibitively expensive. Even in the developed nations where they are economically available, there is growing objection to their prolonged use in agriculture because of their residual damage to the total environment (Arnon, 1984). Provision of adequate amount of durable residue mulch (4-6 tons/ha) may be unpractical under our prevailing climate. On the basis of these problems which may inhibit the continuous use of no-tillage in farming, a system of rotational tillage involving the alternation of no-tillage with conventional tillage systems was evolved by Aina (1988, 1993). In a comparative study involving the different tillage rotational systems, it was observed that soil deterioration generally increased relative to the length of conventional-tillage phase in rotation and depended on the cropping system. A rotational system involving one year of conventional tillage following every two years of no-tillage under maize-cowpea system caused less soil deterioration with higher grain yields compared to continuous conventional tillage system. The study showed that a minimum of four years of no-tillage will be required to offset the level of deterioration imparted by two years of conventional tillage.

Soil erosion by water is a major problem with soils under continuous cultivation in the region. The initial precursor process of particle detachment is enhanced by plow-based tillage which breaks down soil into finer particles thus accentuating erosion process. In a given situation, erosion is characterized by soil erodibility (soil's potential to erode), climatic (rainfall) erosivity (propensity to cause erosion), landform and land use. It results in extensive land degradation through physical removal of the productive topsoil, selective removal of soil nutrients, fertility depletion, and loss of agricultural productivity which is manifested in drastic yield reductions, flooding and siltation of bottomlands and pollution of surface waters by agro-chemicals and sediments. From extensive research of the cause-effect relation of erosion Aina *et al* (1977), Aigbomian and Aina (1981), Oyedele and Aina (1989) showed that the high erosion potential of the humid and sub-humid tropics to the unfortunate combination of high soil erodibility and fragility and high rainfall erosivity. Soil with low organic matter, low free iron oxides and some permanent charges easily disperse upon wetting and are consequently highly susceptible to erosion. Soil vulnerability to erosion is also high as indicated by the low soil tolerance values (i.e. the maximum limit of soil loss that would not adversely affect soil productivity), ranging from 0.2-3.6 ton ha^{-1} yr^{-1} which contrast with a range of values of 5-15 ton ha^{-1} yr^{-1} in the US

(Wischmeier and Smith, 1979). The high rainfall erosivity of the region is due to high energy load of rainfall which is attributed to high rainfall intensities and predominance of large raindrops. We established in the studies that peak intensities in excess of 200 mm hr^{-1} are common, with high kinetic energy loads, related to intensity in a quadratic manner. Predominant drop sizes are usually in excess of 3 mm especially at rainfall intensities above 40 mm hr^{-1} (Aina *et al* 1977; Aina, 1980;). It is believed that high velocity (sometimes as high as 55 knots) usually accompanying most rains contribute to the high energy load. Aina *et al* (1977) in an earlier study at Ibadan observed an increase in median raindrop size with increase in wind velocity.

We have consequently observed from the studies high annual soil losses averaging 90-250 ton ha^{-1} (equivalent to 7-20 tipperloads of soil) and runoff reaching 42% of annual rainfall under cultivation in parts of western Nigeria with severe consequences on crop yields which fall exponentially as erosion increases (Lal, 1984; Sattaur, 1989). Aina and Egolum (1980) in a study by artificially removing varying thicknesses of topsoil, simulating an advanced stage of erosion from a soil freshly opened up from a 25-yr fallow at Ife, reported a 50% reduction in maize yield for a loss of 10cm of topsoil. When erosion has advanced to a certain stage, soil productivity would not be fully restored even by heavy applications of fertilizers. This is because the soil would have lost much of its water-holding capacity due to compaction while the water-use efficiency of the crop declines due to restricted root penetration. Although evidence of severe soil degradation by erosion is highly visible from the occurrence of spectacular gullies, sheet erosional losses on croplands are less noticeable even though the impacts on soil productivity can be very substantial. For example, a 50 t/ha soil loss corresponds to a soil depth reduction of only 3-4 mm, which would hardly be noticed by the cultivator even if he were convinced of their occurrence. However, because of the shallow nature of our topsoils, the loss of the top few millimeter of soil, where organic matter, nutrients and biological activity are concentrated, may therefore significantly decrease soil productivity and crop yields. Thus, for some shallow Alfisols in Nigeria, a loss of 10 cm of soil has the effect of reducing corn yields by 50% (Aina and Egolum, 1980).

It is projected that nationwide, magnitudes of erosional impacts reported from our studies will translate to substantial economic losses of between 250 and 500 million dollars annually. Off-site erosion impacts are more difficult to estimate in monetary terms but they impose more severe social costs on society because they constitute serious threats to life and property and manifest in the pollution and impairment of the quality of the environment (eg NO_3 pollution), siltation and depletion of the storage capacity of water reservoirs and flooding of rivers.

MANAGEMENT PRACTICES TO CONTROL SOIL DEGRADATION

The high vulnerability of soils and limitations to sustainable use especially for food production are thus related to the poor soil physical regimes and dynamics which are associated with weakly developed and easily-degradable soil structure. Because soil structural development and stabilization are attributed mostly to organic matter binding, loss of organic matter will lead to disaggregation and adjunct degradational processes including sub-optimal soil temperature regimes, compaction, increased susceptibility to dispersion and erosion, reduced moisture retention potential etc. The following management practices have been researched with the objective of evolving appropriate methods for sustainable use of the soils. Aina (1981) reported the beneficial effects of mulching with plant residues on soil properties which resulted in 22-63% increase in yields, attributed to the protection of soil surface against climatic elements thus enhancing favorable soil temperatures especially at seedling stage, improved rainfall acceptance and soil water storage in the root zone, better aeration, weed suppression and faunal activity. However to be beneficial in the region, according to Aina (1981), mulching has to be procured at an optimum rate of 5 ton ha^{-1} and early in the season (within the first seven days planting) and for a duration of not less than 6 weeks. (Fig. 6).

The practice of mixed cropping, i.e. growing more than one crop in the same field simultaneously, provides a continuous plant cover over the soil for most of the year and protection against raindrop' and erosional impacts especially when the practice is accompanied with good agronomic practices such as optimum plant population, appropriate plant combinations, adequate pest control and good fertility maintenance. Aina *et al* (1977) reported that soil loss and runoff were significantly lower by 30%, and crop yield higher by about 25% under a mixed cropping of cassava and maize compared to cassava mono-culture. This observation was attributed to differences in cover characteristics which influenced rainfall interception. It was reported further that to attain 50% canopy cover will require 38 days for soybeans, 46 days for pigeon peas (*Cajanus cajan*), 51 days for maize-cassava mixed cropping and 63 days for cassava mono-culture, and rainfall interception at 90% equivalent canopy cover was 50% in

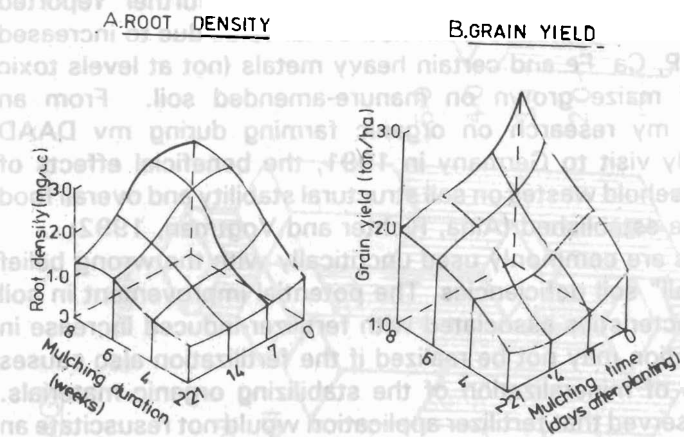

Fig. 6: Effects of Time of Application and Duration of Mulching on (A) Root Density and (B) Grain Yield of Maize (Aina, 1981)

soybean, 40% in maize-cassava and 28% in cassava.

Soil physical properties can be ameliorated through organic and inorganic soil amendments. The practice of manuring of soil is compatible with integrated arables and live-stock farming., The potential of feedlot manure in soil amelioration was demonstrated by Aina and Egolum in 1980. In the greenhouse study that involved manure amendment of normal topsoil and de-surfaced soil (Fig. 7), we observed that complete yield recovery, that is, yields comparable to those on normal productive soil, could be achieved on desurfaced soils by the combined application of NPK-fertilizer and 6% (w/w) feedlot manure. Aina (1983) reported similar effects for poultry manure applied to field degraded soils. The beneficial effects of manure were attributed to increases in the organic matter level, proportion and water-stability of aggregates >0.5 mm, improved soil tilth, pore size distribution infiltration and moisture retention. Aina (1981) further reported additional benefits of improved grain nutritional value due to increased contents of N, P, Ca Fe and certain heavy metals (not at levels toxic to humans) of maize grown on manure-amended soil. From an opportunity of my research on organic farming during my DAAD sponsored study visit to Germany in 1991, the beneficial effects of composted household wastes on soil structural stability and overall food production were established (Aina, Richter and Vogtman, 1992).

Fertilizers are commonly used uncritically with the wrong belief of correcting "all" soil deficiencies. The potential improvement in soil structural characteristics associated with fertilizer-induced increase in biomass production may not be realized if the fertilization also causes increased rates of mineralization of the stabilizing organic materials. Aina (1979) observed that fertilizer application would not resuscitate an already physically degraded soil.

With irrigation being rare and expensive, thus making agriculture in the region highly vulnerably dependent on the vagaries of climate, another basic approach to soil and crop management is to select crop cultivars that are tolerant to drought. Fapohunda, Aina and Hossain (1984) reported seasonal water requirements averaging 45 and 58 cm for cowpea and maize, respectively at Ife, which matched the high evapotranspiration values in the area. Crop response to drought is related to the root system development which in turn influences water uptake by plant. In addition to that of crop water requirements, knowledge of rooting pattern and water uptake by plants is therefore important in reducing plant susceptibility to drought, optimizing water use or selecting improved crop cultivars. Aina and Fapohunda (1986)

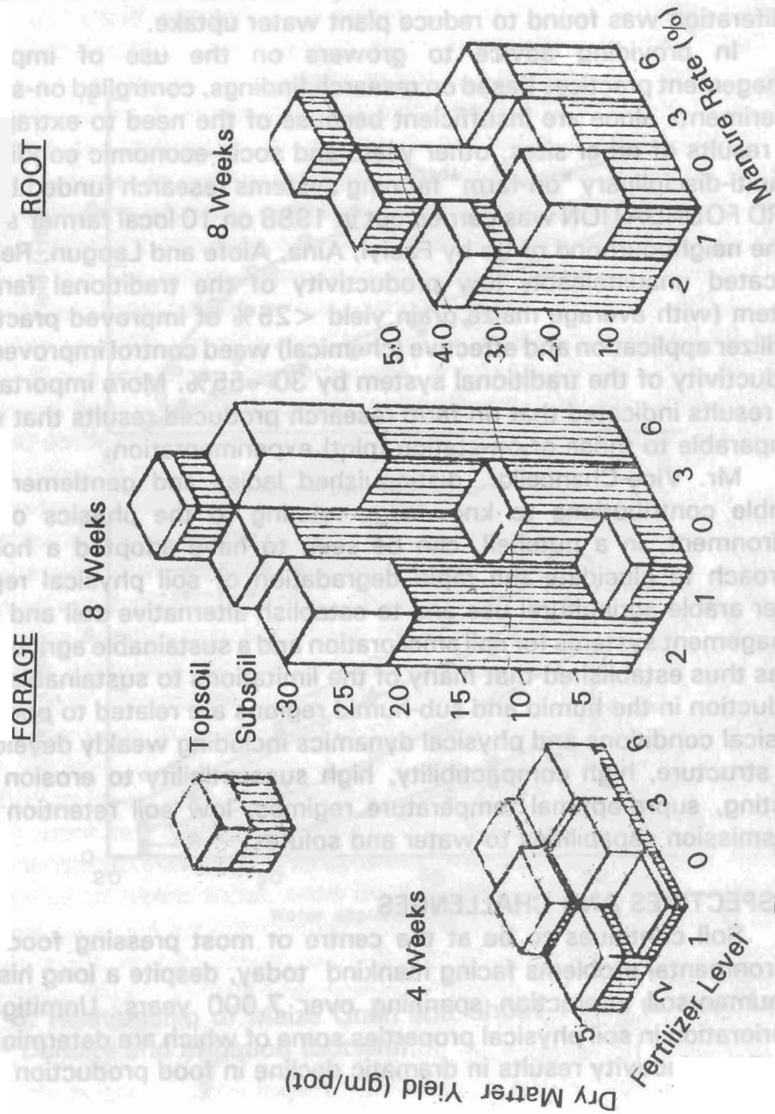

Fig. 7: Effects of Feedlot Manure and Inorganic Fertilizer Amendment on the Improvement of Subsoil Productivity (Aina and Egolum, 1980)

determined rooting and water uptake patterns for three improved maize cultivars, field-grown under several irrigation treatments. Our results (Fig. 8) showed that at adequate soil moisture, yields were closely related to root length density (averaging 2.56, 1.88 and 1.70 cm cm^{-3}, respectively) and average seasonal water uptake (4.2, 3.0 and 2.8 mm/day, respectively), which in turn are related to the soil physical regime. A restrictive soil matrix that impedes water movement and root proliferation was found to reduce plant water uptake.

In providing advice to growers on the use of improved management practices based on research findings, controlled on-station experiments alone are insufficient because of the need to extrapolate the results of other sites, other years and socio-economic conditions. A multi-disciplinary "on-farm" farming systems research funded by the FORD FOUNDATION was carried out in 1988 on 10 local farmer's farm in the neighbourhood of Ife by Fabiyi, Aina, Alofe and Laogun. Results indicated unsustainably low productivity of the traditional farming system (with average maize grain yield <25% of improved practice). Fertilizer application and effective (chemical) weed control improved the productivity of the traditional system by 30 - 55%. More importantly, our results indicated that on-farm research produced results that were comparable to those of on-station (plot) experimentation.

Mr. Vice-Chancellor, distinguished ladies and gentlemen, my humble contributions to knowledge relating to the physics of soil environment, in a nutshell, can be seen to have adopted a holistic approach to elucidate the rapid degradation of soil physical regime under arable agricultural use and to establish alternative soil and crop management systems for soil amelioration and a sustainable agriculture. It has thus established that many of the limitations to sustainable crop production in the humid and sub-humid regions are related to poor soil physical conditions and physical dynamics including weakly developed soil structure, high compactibility, high susceptibility to erosion and crusting, supra-optimal temperature regimes, low soil retention and transmission capabilities to water and solutes.

PERSPECTIVES AND CHALLENGES

Soil continues to be at the centre of most pressing food and environmental problems facing mankind today, despite a long history of human-soil interaction spanning over 7,000 years. Unmitigated deterioration in soil physical properties some of which are determinants of soil productivity results in dramatic decline in food production.

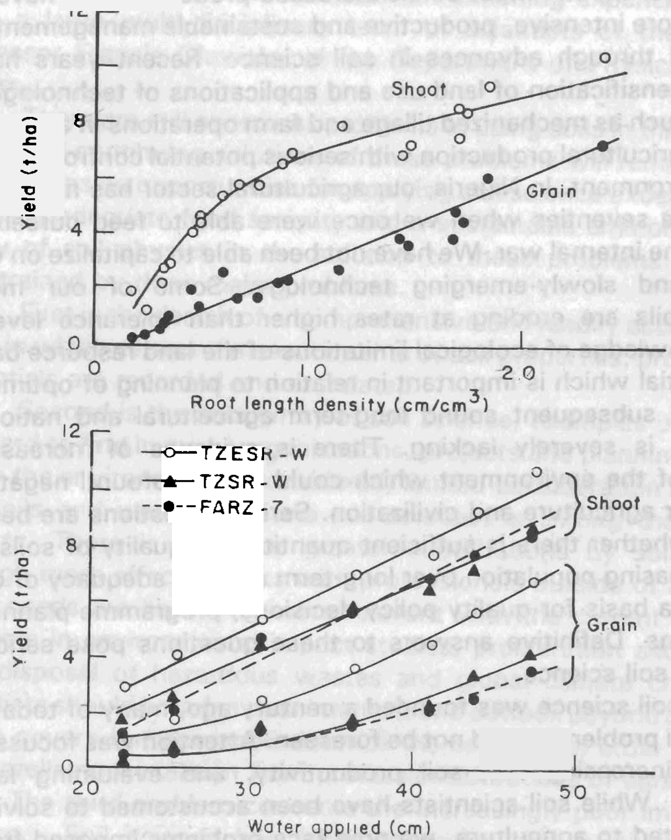

Fig. 8: Relationship of Maize Grain and Shoot Yields to Root Length (top) Density and Irrigation (bottom)

Because important environmental problems are also controlled by the soil e.g soil's capacity to transmit, store and react with solutes including salts pesticides and wastes, soil physical properties are also implicated in environmental problems.

The need for better understanding about soil and for its wider dissemination is not new, but I believe that it is becoming more urgent with time. World population at present is 5.5 billion and highest in the developing world. If the food is needed to be grown there, current yields must be increased considerably above the present subsistence level with lower inputs. Most of the increased production will have to come from more intensive, productive and sustainable management of the soils and through advances in soil science. Recent years have witnessed intensification of land use and applications of technological innovations such as mechanized tillage and farm operations in attempts to increase agricultural production with serious potential confrontations with the environment. In Nigeria, our agricultural sector has not had a leap since the seventies when we once were able to feed ourselves even during the internal war. We have not been able to capitalize on our knowledge and slowly-emerging technology. Some of our most productive soils are eroding at rates higher than tolerance levels. Adequate knowledge of ecological limitations of the land resource base and its potential which is important in relation to planning of optimum land use and subsequent sound long-term agricultural and national development, is severely lacking. There is evidence of increasing degradation of the environment which could have profound negative effects on our agriculture and civilization. Serious questions are being raised over whether there is sufficient quantity and quality of soils to feed our increasing population over long-term and the adequacy of our resources as a basis for quality policy decisions, programme planning and projections. Definitive answers to these questions pose serious challenges to soil science.

When soil science was founded a century ago, many of today's environmental problems could not be foreseen. Attention was focussed firmly upon increasing crop-soil productivity, and evaluating land development. While soil scientists have been accustomed to solving problems related to agriculture, we now face problems imposed from larger human community. Currently there is great concern about the environment and even the possibly undesirable effects that intensive crop production methods may have upon the environment. Modern society generates horrendous amounts of wastes which pollute the soil and affect soil's agricultural productivity. Faced with an increasingly

acute problem of waste disposal, there is even growing interest in the possibility of applying such waste materials to soil. As humans now have the increasing capability of quickly degrading the soil and polluting the environment, in the immediate future, soil science will have a major role to play in mitigating the problematic effects of environmental degradation, in addition to increasing soil productivity on sustainable basis. On this premise, my conception of the physics of soil environment got broadened later in my career to include environmental impact investigations of industrial and development activities that involve the use of soil. It has been an enriching experience working with a large multi-disciplinary team of scientists of the stature of Professor Francis Oluwole, of the Department of Physics and many others.

There are still enormous problems in using soils in this part of the world and continuing solutions of those problems will remain essential with increasing opportunities for applying soil science exoertise toward ensuring adequate food security and a sustainable environment. The utility of soil physics in the solution to these problems is however constrained by three major problems.

First is the dearth of a comprehensive and readily accessible data bank in which all sound measurements of soil properties, processes and potentials are recorded and correlated.

Second is the anonymity of soil science, examples of which are not hard to find in many organizations, projects and plannings in which when the environment is considered, limited consideration is accorded the soils and usually not one soil scientist is among the bodies of experts. There is need for greater contributions by soil scientists through more effective links with professionals outside of agriculture. Such needs are becoming more relevant with the current upsurge of interests in environmental impact studies, proliferation and means of safe disposal of hazardous wastes and global climate change. Soil scientists should broaden their interests and outlook beyond agriculture, which covers but one application of the science, in order to prevent their intellectual isolation from professionals outside of agriculture.

The third problem concerns the increasingly poor image of soil science. Soil science has failed to excite and sustain the same interests. Our output of soil science students is low and in fact declining. Here in Obafemi Awolowo University for instance, the number of soil graduates in each year from 1982 to 1992 is only a little over 17% of the total number of graduates in agriculture. Shortages of adequately trained professionals are also becoming apparent and are projected to worsen. The poor image has significance for several reasons. It directly affects the uses of soils and it also affects public policy in matters such as funding, waste disposal, pollution and others. The reason for the poor image has some historical basis. Soil has always been common place and virtually always underfoot and unnoticed. Although it was one of the first natural resources to be used by mankind, it was among the last to be given scientific study. Soil has been taken for granted for a long time.

If soil science is to continue to prosper and be attractive, and meet the various public demands for safe and sustainable agriculture. better land use and improved environmental quality to meet the requirements of future generations, the role of soil science must be broader than just improving food production but with wider range of applications in the environment. . This will have to be complemented with more trained soil scientists with a good background not only in the basic sciences of physics, mathematics, chemistry and biology but also a thorough understanding of their interplay in the soil system. Soil scientists must be more robust and strengthen their visibility, become more interested in environmental issues and make contributions toward their resolution. The need for research or involvement on these effects would not lessen but enhance the importance of continued research to maintain the capacity of soils for producing food and fiber.

CONCLUSIONS

In conclusion, Mr Vice-Chancellor, distinguished ladies and gentlemen, a healthy and productive soil resource is the foundation of any nation's agriculture which is the economic engine for most activities. Consequently, any threat to the supply or quality of soil constitutes a threat to our enduring food base, our civilization and existence. As aptly put 55 years ago by President Franklin Roosevelt of America "A nation that neglects its soil endangers its own survival."

Soil physics has made significant advances in the past century in the understanding of soil physical properties and processes which control the biological health of soil and the operative laws governing them and that of the soil-plant-atmosphere interactions, with the goal of enhancing crop-soil productivity. With increasing problems of wastes generated by the modern society's industrial, transportation, agricultural and other activities which have the potential of polluting the soil and affecting its productivity, soil physics has an increasing role of mitigating the problematic effects of environmental degradation.

Enormous problems still exist in using (misusing) the soils in the regions as evident from widespread soil and landscape degradation severe erosion, loss of agricultural productivity and many environmental and soil-related problems which put the fixed supply of land under continual stress. The problems are attributed to insufficient awareness of the existence and severity of soil degradation, inadequate or lack of knowledge and scientific information relating to ecological and soil potentialities and appropriate management of soil physical conditions. Soil is consequently at great risk and agriculture in Nigeria faces a difficult future unless there is a concerted, coordinated and cooperative effort to overcome the problems of soil degradation.

RECOMMENDATIONS

Solving Nigeria's pressing economic and ecological problems in agriculture and environment will require the sustainable use of the fragile and vulnerable soils. A progamme of actions to attack the problems, it seems to me needs, include the following:

1. The land base for food production must be given the prominence it deserves by means of a national framework and public education to enhance adequate scientific information on ecological characteristics, soils, their spatial distribution, potentialities and limitations, and types and extent of degradational processes.
2. There is urgent need for a national soil conservation programme backed up by appropriate public policies regulating land use and husbandry.
3. Implicit in (2) above, is the need for substantial and sustained (by adequate funding) soil conservation research and training for the development and effective implementation of appropriate conservation practices
4. Soil and soil scientists should be accorded their rightful recognition in matters relating to agricultural and environmental project planning implementation and monitoring.
5. A Soil Conservation Service should be established and charged with the following duties: defining soil conservation objectives, land use ethics, giving direction and scope of research need in soil conservation and soil management, for the control of erosion and other forms of soil degradation and development of ecologically sound and economically acceptable soil conservation practices and enforcing the adoption of the practices.

ACKNOWLEDGEMENTS

In bringing this lecture to an end, I want to glorify God for His abundant guidance in my pursuit of a fulfilling career.

I want to express my appreciation to my wonderful, patient, enduring and accommodating wife, and my understanding children. I have considered myself particularly fortunate to have been able to enlist the participation and support of several most highly regarded colleagues and students especially in my Department and Faculty here at OAU and at various other places in and outside Nigeria. I want to acknowledge with deep gratitude the study fellowships provided variously by bodies including Obafemi Awolowo University, the Ford Foundation, International Atomic Energy Agency, Food and Agriculture Organization of the UN, DAAD and the United Nations University which have been very supportive to my academic career.

Mr Vice-Chancellor, distinguished ladies and gentlemen, thank you for listening.

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