CONSERVATION-EFFECTIVE FARMING SYSTEMS FOR THE SEMI-ARID TROPICS

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FARMING SYSTEMS RESEARCH PROGRAM
SOIL PHYSICS AND CONSERVATION

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SUMMARY

Soil losses by erosion and water losses as unctrolled runoff have clear and immediate impacts on farm productivity. The interrelationships between erosional losses and productivity are consistent and quantitatively predictable. Soil and water conservation, therefore, is deeply relevant to ICRISAT's FSRP mandate. A systematic conceptual framework for a research program on soil and water conservation and management is outlined in this document.

The proposed research will consist of two major elements. The first is to establish needed values of the inherent site characteristics which enhance the erosion of soils in the SAT, i.e., base-line data for quantitative assessment of soil loss and runoff potentials. The second is to determine, quantitatively, the modifying influence of alternative management practices on these potentials. Among these, we will give particular emphasis to land and soil treatments which impart long-term residual effects through improved soil structural characteristics.

Certain important problems remain, and new ones arise, on Vertisols; these should be investigated. However, the majority of our management studies will be focused on Alfisols.

CONSERVATION-EFFECTIVE FARMING SYSTEMS FOR THE SEMI-ARID TROPICS

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I. INTRODUCTION

Conservation of soil and water is the key to sustained productivity in any agriculutral enterprise. This is particularly so in regions, such as the semi-arid tropics (SAT), where water supply is limiting. Even under undisturbed conditions, water and wind erosion hazards in the SAT may be the highest of any agro-climatic zone. This is primarily due to the lack of sustained vegetative growth during the dry season and subsequent lack of protective cover at the onset of the wet season. High rainfall erosivities and soil erodibilities are added factors which increase erosion hazards in these regions.

Soil losses by erosion and water losses as unctrolled runoff not only reflect the inherent unproductive nature of the prevailing farming systems in SAT environments but themselves lead to further deterioration of land productivity. One of the elements of ICRISAT's mandate, therefore is to :

- DEVELOP IMPROVED FARMING SYSTEMS THAT WILL HELP TO INCREASE AND STABILIZE AGRICULTURAL PRODUCTION THROUGH MORE EFFECTIVE USE OF NATURAL AND HUMAN RESOURCES IN THE SEASONALLY DRY SEMI-ARID TROPICS

This statement defines the scope of ICRISAT's Farming Systems Research Program (FSRP) whose primary aims are to:

- Describe and classify the agronomically relevant features of the soil and climatic resources of SAT.

- Identify the physical and biological processes that largely determine crop performance in the various agroclimates of the SAT and establish basic principles that describe these processes.

- Develop production practices and systems of farming that will result in improved, stable food production by optimum utilization of the SAT's natural resources.

- Determine regional research priorities by excution of simulation and modelling studies based on climatic, soil, and cropping systems data.

The ICRISAT 10-year plan has identified as a priority area the development and refinement of alternative natural resource management techniques for important SAT soils (1).

While soil and water conservation must not be considered as an end in itself, it is deeply relevant to the carrying out of ICRISAT/FSRP goal and priority objectives. A systematic research program on Soil and Water Conservation which combines the collection and assessment of resource base-line data together with resource management for optimization of productivity and which builds on the past achievements and present strengths of ICRISAT is outlined here. The framework is primarily research-focused but recognizes certain service and operational/demonstration scale activities as vital elements of interaction with other subprograms within and without FSRP.

II. EROSION'S ROLE IN FARM PRODUCTIVITY IN THE SAT

The following discussion is primarily centered around soil losses as a result of erosion by water. However, since overland flow and surface runoff are requisites to erosion phenomena, erosional water losses as runoff are also often implied. Wind erosion is also determined by parallel factors to and produces impacts similar to those of erosion by water.

II. A. Erosion Potential in the SAT

A global analysis of soil erosion trends in different climatic zones shows the major rainfall erosion hazards to lie mainly in the tropics and subtropics. Within these areas, the water erosion hazard is least in arid zones where rainfall is rarely capable of meeting vegetative requirements, saturating the soil, and producing runoff. Wind erosion hazard, however, may be severe in these areas. On the other end of the rainfall specturm, erosion hazard is very high in the humid tropics. Interestingly, however, actual erosion is usually negligible in these locations due to characteristically abundant natural vegetation, so long as this has not been disturbed by man. The high erosion potential is manifested as soon as such disturbance is imposed e.g. by deforestation. However, abundant water supply favors rapid re-establishment of many forms of protective vegetation.

With their intermediate rainfall amounts and distinct seasonal distribution, the semi-arid tropics may well posses the highest erosion hazard of any rainfall zone. Available schematic representations for undisturbed conditions show erosion to peak at about 750 mm of annual rainfall (12, Fig. 1). This may be explained by the collective contribution of various factors. First, the SAT generally lack the abundance in water supply needed to sustain the permanent vegetation which provides necessary cover for soil protection against erosion. The sparse and fragile vegetation remaining at the end of the dry season provides little protection against erosion upon arrival of the rainy season. Secondly, there is some evidence that the less intensively weathered soils of the SAT, e.g. Alfisols, Vertisols, and Entisols, are more erodible than those of the humid tropics e.g. such as Ultisols, Oxisols (7, Table 1). Among the additional likely factors is the highly agressive nature of rainfall in the SAT despite the short rainy season.

It is important to note here, however, that a full quantitative analysis of rainfall erosion potential in the SAT has yet to be done. A framework for conducting such an analysis will be presented in section IV.

II. B. Erosion Impacts on Land Productivity

For a thorough assessment of impacts, land productivity should be considered in its wide context to encompass all the benefits associated with the use of a defined land resource unit or ecosystem. This may be best exemplified by a self-contained or independent river basin comprised of catchment areas, downstream areas, and ultimate outlets to low-lying lands, estuaries, or the ocean. Documentation, therefore, must integrate the effects on all the sources and destination points of erosional sediments. These are often referred to as on-site and off-site effects. The failure to recognize all the effects collectively is responsible for the lack of accurate determinations of "soil-loss tolerances" or t-values, i.e. those losses which should not be exceeded in order for productivity to be sustained indefinitely. Tilerable soil loss values (which will be designated here as T.L.) are often used as a basis for judging the serionsness of ongoing erosion and the need to undertake remedial or control measures. There is a common tendency among those land users whose interests lie in a small segment of the ecosystem to be concerned only with the quality of that segment. In contrast the policy maker or land use planner must consider all effects simultaneously, for instance, erosion's effects on soil productivity and sedimentation effects on the life-longivity of reservoirs or fisheries. In this document, as we must, we will restrict our discussion to farm productivity aspects particularly under SAT conditions.

"Resource-deprivation" is the basic reason for the detrimental effects of soil erosion on farm productivity.

As far as the soil resource is concerned erosion removes valuable nutrients and organic matter, reduces the depth of physically favorable "top-soil", reduces the overall soil depth available for root profileration, diminishes soil-water and nutrient storage and availability, exposes soil layers that are chemically and physically inferior as a medium for crop growth, and, in the long run, results in irreversible soil degradation and landscape denudation (7, Table 2).

No net soil erosion is likely to occur from the farm unless sediment is transported by overland flow. Implied in accelerated erosional losses, therefore, are water resource losses as unctrolled runoff. Where water supply is limiting, the and subsequent lack of water entering as soil storage or as replenishment to usable ground-water may lead to exaggerated droughts, even in seasons with adequate rainfall. Therefore, erosional losses of both soil and water must be considered as equal causes of decline of the land's agricultural productivity in the semi-arid tropics.

II. C. Conservation Effectiveness as an Index of farm Productivity

Due to the collective contributions of the parameters discussed above, there is good reason to conclude that the productivity of a farming system is largely dependent on its effectiveness in conserving vital physical resources, i.e. the extent to which erosional losses of soil and water are effectively controlled. Interestingly, the reverse of this statement is also correct as erosional losses are, in turn, also dependent on productivity. Healthy and well managed stands of vegetation display a higher efficiency in resource utilization and provide more effective protection against such losses than do poor stands. The consistent and predictable nature of the erosion-productivity inter- relationships favors a proposal to use "conservation-effectiveness" as an index of the overall productivity of the farming systems.

The Conservation Effectiveness Index (C.E.I.) may best be expressed as a ratio between "tolerable" loss (T.L.) for a given site, and erosion loss (E.L.) actually encountered or predicted for the site under a defined set of management practices.

Thus, $$\text{C.E.I.} \qquad \frac{\text{T.L.}}{\text{E.L.}} \qquad (1)$$

The index should be applicable to either soil or runoff losses and its interpretation for a given site (with a designated T.L.) would be based on the fact that its absolute value increases with the effectiveness of imposed management. Specifically, the system in place is conservation- effective if the index is one or more (C.E.I. ≥ 1) and ineffective if less than one (C.E.I. < 1).

The utility of this concept to farm productivity follows from the fact that a management plan which allows "intolerable" erosional losses will produce continuous declines in productivity and ultimate soil degradation. On the other hand, a plan which, through manipulation of appropriate management parameters maximizes the control of erosional losses, will also likely maximize farm productivity. Naturally, differences in soil and crop tolerance limits will also be reflected by the index so that the more fragile the soil, and drastic crop response to these losses, the lower is the index for a given rate of erosion. Low values, particularly < 1 call for urgency in imposing corrective measures.

A parallel argument may be made for losses of water by runoff. However, the difficulty in this case is to determine T.L. values with view of those components of the water balance equation which are critical to crop performance, e.g. soil water storage and recoverable seepage.

II. D. Short and Long Term Benefits

Much of the recent quantitative analyses of and models for productivity dependence on erosion have originated in developed countries, primarily the U.S. The two most advanced among these are the EPIC (erosion productivity impact calculator) and the productivity index model (17, 28). A major conclusion of such models is often that erosion impacts are small and very long-term in nature; yield declines of less than 20% are often projected after 50 years of above "tolerable" erosion. For example a 12% decline in yield is projected for sorghum in a cotton-sorghum-wheat rotation on Houston Black soil, a Vertisol very similar to ICRISAT Center's Kasireddipalli series. This despite a continuing annual soil loss of approximately 27 T/Ha.

It would be hard to get excited about such impact should they also hold in developing countries. Certainly the validity of the above arguments diminishes if this scale of projection was indeed universal. However, it is not. Two components are primarily responsible for the lack of sensitivity in productivity response to erosional soil losses in highly technological settings. First is that a continuation of the high current management input levels for optimum production are assumed in the analyses. These levels are such that the farmer is annually (still) able to copensate for nutrient and water losses and to restore favorable root-zone depths to meet his crop's requirements. For these he practices optimum fertilization (and supplemental irrigation) and tillage. Second, and equally important in the SAT, is that while changes in the capacity of soil for water storage as a result of erosion are accounted for, the runoff control element of productivity appears to be ignored by these models.

When the small farmer of the SAT is considered as the focus of concern, the above picture changes drastically. There is indeed abundent evidence that effective erosion-control systems in the developing countries, both in the SAT and elsewhere, have very dramatic short-term benefits. This is predictable by the fact that affordable inputs are low and, subsequently, soil loss tolerances are small. This will drastically reduce C.E.I. values and productivity. The gains from implementing conservation measures, therefore, should be high and immediate. In the SAT, both soil and water elements will contribute to these gains (15, 20 Table 3).

In-between the two extremes of highly developed and subsistence farming, investigations for effective resource use should enable users to make a realistic assessment of erosion impacts. This requires the flexible setting of tolerance limits so as to allows for varying levels of necessary management inputs.

III. SOIL CONSERVATION PLANNING AND MANAGEMENT OPTIONS

Land use planning which is based on both the soil's attributes and limitations is requisite to successful agriculutral use. Since "prevention is better than cure", lands with high erosion potential should be developed for cultivation only with great precautions; in the extreme natural forest vegetation on steep slopes should not be at all disturbed. Qualitative and quantitative estimations of erosion potential for a given site are possible with the use of certain characteristic data. Should the estimated soil loss for the site exceed the threshold value, above which sustainable soil productivity is threatened (soil-loss tolerance), then land use must be accompanied by preventive management practices. Clearly, therefore, the setting of target tolerance values is a crucial step in land use planning and must be made with a careful consideration of all the impacts discussed earlier, particularly changes in soil productivity. In the rainfed SAT, runoff losses associated with soil erosion must be important components of determined tolerance values.

III. A. Rainfall Erosion Prediction and Control Parameters

Kinetic energy provided by rainfall and/or runoff is the initial force in any erosional process resulting in the detachment of soil particles from the remaining soil mass. Transport of the detached particles to a new destination completes the erosion process. Clearly, therefore, factors which enhance detachment or transport enhance erosion by water. These may be summarized as:

- o High quantity, intensity and long duration of rainfall
- o High volume and velocity of overland flow
- o Poorly structured, slowly permeable, and easily detachable soils
- o Steep topography and long slopes
- o Sparse vegetative cover and/or insufficient organic residue

- Tillage practices and land surface configurations that are inducive to a high volume and increased velocity of runoff

These factors interact to collectively determine the ultimate soil and water losses by erosion from a given field. Quantitatively, they have been combined in a variety of models designed both to predict erosion, based on values determined for each factor, or control erosion, based on the possible modification of values for those factors that are amenable to management.

For the forms of erosion which are important in crop lands (rill and interrill or sheet erosion), the universal soil loss equation (USLE) is the most advanced and tested model. This equation has the form:

$$A = R\,K\,L\,S\,C\,P \quad \ldots\ldots \quad (2)$$

and states that the soil loss (A, tons/unit area) are determined by six factors; rainfall erosivity (R, erosivity units), soil erodibility (K, tons/ unit area/erosivity unit), slope-length and gradient (L, and S, expressed as dimensionless factors), cropping management (C, dimensionless) and land practices/configuration (P, dimensionless). The dimensionless factors are quantified by using, as a base, a unit standard plot whose slope steepness is 9% (S = 1), slope length is 22.1 m (L = 1), and which is strictly bare fallow (C = 1), with straight row cultivation practices directed along the prevailing slope (P = 1).

The USLE is universal only insofar as it identifies all the parameters that determine the magnitude of soil loss due to rill and interrill erosion and, therefore, allows for manipulation of appropriate parameters for erosion control. It has been successfully applied to many locations within and outside the U.S., but has also received considerable ministerpretation, and therefore, misuse. The primary misuses of the equation arise from attempts of various workers to utilize it directly outside its intended scope (namely "adoption without adaptation"), a problem which may be partially blamed on its name. To be successfully applied for soil loss calculations, the equation must use factor values specifically applicable to the site in question and must be used on a long term basis in order to allow the averaging out of irregular, temporal fluctuations in factor values. Its applicability to single storm events or short term trends is limited by the non-stable and cyclic nature of weather, particularly rainfall patterns (and thus R values), fluctuations in antecedent water contents, surface conditions, and storm characteristics (and thus K values), and variations in crop performance within the season and between seasons (and thus C values). There are certain other precuations which must be observed when applying the USLE; perhaps most important is the fact that the equation must be specifically modified to estimate sediment delivery from soil loss data, to incorporate runoff erosivity within the R factor when necessary, and to predict short-rather than long-term soil losses.

On the socio-economic side, the USLE is an insufficient tool for implementing soil conservation as it does not adress the "non-technical" factors which clearly contribute to the problem and act as constraints against remedial measures.

The above limitations are not inherent only to the USLE, but to many models which followed suit. SLEMSA, the Soil Loss Estimation Method for Southern Africa (8) is perhaps the closest rival, though still far behind in testing and verification. Specific modifications of the USLE have been and continue to be, made by various workers to make it suitable for specific uses which were not intended intially. The MUSLE (Modified Universal Soil Loss Equation) allows for estimating sediment delivery for single storm events rather than average soil loss on a long term basis (14). However, the equation emphasizes runoff erosivity at the expense of neglecting rainfall erosivity. Other adaptations attempt to extend the use of USLE to non-crop lands, such as forest areas (4) for which parameter interpretations and sub-parameter components are distinctly different from cropped fields.

The above limitations of the USLE not withstanding, the integration of all the above factors in a single model to predict and control erosion makes it amenable to use as an overall conceptual framework for optimization of land productivity through manipulation of those parameters in the equation which can be readily managed. This conceptual framework is very consistant with "watershed-based" planning of farming systems and, indeed, *provides an analytical base for such planning.* An analytical base is important for extending ICRISAT's valuable experiences to new situations by quantifying the likely effects of "adaptive modifications" on watershed performance.

III. B. Required Information

A close examination of the proposed framework reveals that two sets of data are required for its utilization. The first set includes all the inherent site characteristics, namely the rainfall (R), the soil (K), and topography (L, S). The second includes the management parameters whether pertaining to the land management practices (P) or cropping systems (C). While topography is frequently altered in land preparation for farming, the C and P factors must be emphasized on small farm scale as they are clearly within the reach of the subsistence farmers. This is particularly true *for mild topographies* such as those which appear common in the SAT.

III. B. 1. Rainfall erosivity -- The ability of a given rainfall to cause erosion depends on its ability to both detach soil particles and to induce sufficient runoff for transporting detached particles. Rainfall kinetic energy (primarily determined by its quantity), drop size distribution, and intensity are, therefore, the components necessary to quantify rainfall erosivity. These being interrelated, it has become convenient to develop empirical relationships directly between a collective erosivity index (R) and soil loss. The most successfull indices have used storm kinetic energy (e.g. $K.E. > 25$, representing the kinetic energy of storms with a total rain exceeding 25 mm), or have combined this with some measure of storm intensity (e.g. EI30, the product of storm kinetic energy and the maximum 30 minute intensity). The EI30 has been tested in many locations around the globe and appears to have rather wide applicability. Where rainfall is less intense, such as in Hawaii, intensities over longer duration were found adequate for replacing I30. However, the opposite is true for locations with intense storms as appears to be in the case in the SAT areas of Africa and Asia.

Because of difficulties and expense of obtaining direct raindrop size distributions for various storms, empirical equations are often used to calculate storm kinetic energy or K.E. (29). The most common of these is:

$$K.E. = 916 + 331 \log I \qquad \text{(Ft-ton/acreinch)} \quad ..... \; (3)$$

Equation (3) is the U.S. form in which I is the intensity (in/hr). In metric units the equation reads:

$$K.E. = 210 + 89 \log I \qquad \text{(tonne-m/ha. cm)} \quad ..... \; (4)$$

in which I is expressed as cm/hr. For S.I. units:

$$K.E. = 0.119 + 0.0873 \log I \qquad \text{(megajoule/ha/mm)} \quad ..... \; (5)$$

in which I is expressed in mm/hr.

Because of the fact that drop size distributions have been found to display no change above $I = 3$ in/hr, the maximum K.E. values from the above equations for one inch of rain are 1074, 289, and 0.283, respectively. To our knowledge this empirical equation has not been specifically verified for SAT rainstorms.

Several levels of rainfall erosivity information are required for conservation planning. First is the mean annual value for the erosivity index which quantifies its total hazard for the year. Second is the distribution of the index with time during the year which identifies the most critical periods and quantifies the rainfall erosion hazard during each. Third is the frequency distribution for both storm and annual erosivities to allow an estimation of probable maximum values for safe conservation planning.

III. B. 2. Soil erodibility The soil's inherent susceptibility to erosion is determined collectively by its textural, structural and hydrological properties. On the one hand particle detachment and subsequent removal depends on the sizes of primary and secondary particles which make up the matrix as well as on the stability of structural units. On the otherhand, runoff occurance as a result of a given rainfall and its effectiveness in transporting detached particles depend largely on the infiltration and drainage characteristics of the soils. A high soil tendency to form rills by the action of overland flow also appears to increase susceptibility to erosion.

K values, to be inherent to the soil, are experimentally determined as the soil losses induced by a unit of rainfall erosivity under the conditions provided above for standard unit plots (L, S, C, P ; all = 1). Naturally, the dimensions of K will depend on how R is expressed; with equation (3) K would be expressed as tons/acre/U.S. EI30. These are the most commonly found units in the published literature.

Because K depends on soil physico-chemical characteristics, its value can be predicted from appropriate, and simply measured, parameters (7, Fig. 4). Furthermore, although a single K value is usually assigned to a given soil or soil horizon, that value represents an average condition which may not actually occur at any given point in time. Erodibility is, therefore, a dynamic property which changes not only during the course of a year but also over the long term. Some of these changes may be due to natural temporal fluctuations in water content and surface conditions, others reflect true, permanent, changes in soil structural or hydrological properties. This is best exemplified by irrigated soils which undergo an accumulation or removal of exchangeable sodium with continued irrigation or application of amendments. The often noted increase in soil erodibility following forest clearing, however, may be an actual reflection of reduced organic residue content which may be considered a component of the C factor rather than soil erodibility.

The equations which have been most successful for predicting the K factor utilize strong correlations with particle size distribution, aggregate stability and size distribution, structural class, permeability, organic matter content and, particularly for tropical soils, the relative content of mineralogical and bonding constituents. The monograms and predictive equations which have been formulated by various workers for quantitative estimations of the K factor should be used with caution due to the limited data base from which most were developed. K values derived by extrapolating predictive parameters far outside the range used to develop the equations are probably not valid. Experimental determinations of these values, therefore, must receive a priority in the planning phase of a conservation program. Simulated rainfall is often employed to accelarate the collection of such data and to assist in the development of locally-applicable predictive equations or verification of the applicability of equations developed elsewhere (6, Fig. 5).

III. B. 3. Topographic Parameters -- The effects of slope steepness and slope length on runoff and soil loss have received considerable coverage in the literature (19). It is often presumed that these factors are the least site-specific among all erosion causing parameters. Little data is available, however, to support or refute this contention. It is expected that soil specificity would be important in determining the relative role played by direct raindrop impact and overland flow in the erosion of different soils. However, it would appear that the transferability of existing LS data is by and large quite acceptable (10). The major limitation is that this data is experimentally-based only in the range of 3 to 18%; S values for slopes below and above this range represent extrapolations of data. This is true also for L values where slope lengths exceed 122 m. Clearly, verification of the applicability of the existing tabulations is necessary for the relatively flat lands of the SAT as well as the steep lands of the hilly humid tropics.

III. B. 4. Crop cover and residue management -- The combination of crop canopy characteristics, rooting patterns, short-term residue and mulching properties, littering habits, and long-term organic contributions to soil structural development are the primary components of the C factor. To compute this factor one needs quantitative values for these components for the cropping system under consideration during specific time periods. This information is combined with the erosivity risk for each period (see the R factor seasonal distribution) to arrive at a characteristic, e.g. annual, value for the specific cropping system. An effective conservation plan would be to manipulate the system in such a way as to reduce the C value to a minimum. This may be accomplished through the selection and rotation of crops, intercrops, ground cover, residue, incorporation, mulching or the timing of various operations, particularly planting, harvesting, and fallowing with respect to the significantly hazardous erosivity periods. Of importance here is that the many competitive uses of crop residue in subsistance farming necessitate placing an emphasis on not only the quantity of harvestable grain but also the total biomass produced by the crop.

For the same reason, a major new dimension in LDC farming systems which are generally impoverished in residue return to the soil, must be the role of supplementary plantings that are primarily intended to provide a source of vegetative material for C factor optimization. Fast growing legumes, whether annual or perennial will not only benefit erosion control but may also serve as sources of animal feed, fuel wood, or soil nutrients. Many agro-forestry schemes, for example, are intended to provide such benefits (2, 27). among the likely legumes are Sesbania sp., Leucaena sp., Stylothensis sp., and several others. The manner in which such plantings may effectively contribute to overall conservation effectiveness should be studied in relation to overall system design. For instance the shrubs may be most effective when placed in such a way as to stabilize critical field sections, e.g. bunds, against failure under the pressure of excessive runoff. Where wind erosion is problematic, shrub selection and planting design should allow maximum protection.

In general, for low input situations, manipulation of the C factor is considered much more feasible technically, socially, and economically than engineering erosion control options. This is particularly true in SAT agriculture where slope gradients appear to be sufficiently low as to require minimal land shaping. The role of agronomists and soil fertility specialists in optimizing such manipulations cannot be overestimated.

III. B. 5. Land management and support practices -- Land shaping, tillage, and installation of provisions for runoff control and diversion, all are among the components which contribute directly to the P factor. Quantitatively, its value represents the extent to which soil loss from a defined land area is reduced from the maximum which is generally expected for straight up-and-down slope cultivation (P = 1).

Because land shaping practices may alter surface topography, adjustments in L and S values are often necessary to accompany P factor assessment for a full quantification of the effect of a given land configuration. The benefits of contour terracing of steep lands, for example, are explained by collective reduction in the P and LS values.

III. C. Runoff Prediction and Control

As indicated earlier, the factors which enhance per unit area soil losses by erosion and water "losses" as surface runoff are virtually the same. These are rainfall characteristics, soil characteristics, topography and relief, and the nature of land use, particularly prevailing vegetation. The exact manner in which these factors interact, however, has yet to be integrated in a runoff prediction model equalling the USLE (or its relatives) as a model for soil loss prediction. The problem is further complicated by the fact that the experimental data base for empirical modelling allows for insufficient distinction between surface and subsurface runoff from most monitored catchments.

There are predictive approaches which range in scale from the estimation of annual runoff volume to single-storm predictions. Perhaps the most widely used is the curve number method (24) which utilizes, as inputs, storm (or daily) rainfall and catchment storage capacity which in turn depends on soil water content and retention characteristics. This method with plentiful tabulations of supplementary data, is routinely applied for runoff predictions by the USDA Soil Conservation Service. The procedure divides soils into four hydrologic groups (A, B, C, and D) in decreasing order of premeability and increasing runoff generating potential. Three classes of antecedent soil water (dry, average, wet) are also utilized. Prevailing land use in terms of vegetative cover and imposed practices are also distinguished. As for the USLE, the procedure needs calibrations and adjustments for new situations to ensure applicability with some degree of precision. For flat lands common to many AT areas, a special emphasis should be placed on the important role of surface depression storage in determining runoff quantity as well as initiation time.

Peak runoff rates are also predictable by various available models. The most common of these is the Rational Formula which utilizes quantitative values for rainfall intensity, time of concentration, catchment area and overall infiltration characteristics of the watershed (14, 24, 25). Predicting such peak rates is necessary for estimating the quantity and duration of maximum floods which have a high probability of occuring from defined watersheds.

III. D. Sediment Delivery - Soil Loss Relationships

Soil material which is eroded within the confines of a given catchment (gross erosion) is not normally fully discharged at the outlet of the catchment (sediment delivery). This is due to the inevitable redeposition of a certain amount of eroded sediment within the watershed. The fraction of delivered to eroded sediment is defined as the sediment delivery ratio. This ratio is dependent on the characteristics, primarily velocity, of runoff within the catchment and its subsequent ability to carry and transport the eroded material over the full path to the outlet. Existing data show that the ratio increases with decreasing area of the watershed, finer texture of eroded material, steeper topography and fewer drainage channels within it, and with decreasing amount of (trapping) vegetation and plant residues on the land surface (7, Fig. 6).

The USLE does not alone estimate sediment delivery; however it can be modified to do so. The scale of experimentation utilized to collect sediment loss data and determine model applicability must consider the distinctions stated here.

III. E. The State-of-the-Art in the SAT (including ICRISAT's)

III. E.1. Rainfall erosivity -- The Central Soil and Water Conservation Research and Training Institute (2, Fig. 2) has published a tentative erosivity map for India which shows an annual EI 30 contour value for Hyderabad and environs to be 214-250 U.S. EI 30 units. This quantity is small for an annual basis but is considerable when the short rainy season is considered. For the reader's information, the highest annual value recorded in Hawaii and West Africa is 2000, in the U.S. mainland 650, and in India 1500. A seasonal breakdown and a frequency analysis by storm or year are not included. A Dutch group (11) borrowed ICRISAT's rainfall records for a number of years in the mid 70's and analyzed several rainfall intensity parameters and computed average annual EI 30 values for ICRISAT Center and a few other SAT locations in Africa. French workers (21) published an iso-erodent map for West and Central Africa which included annual erosivity data for several SAT countries. EI 30 values of about 290 and 410 were determined for Niamey and Ouagadougou, respectively. Chances are that additional information for other locations may be available in published and unpublished literature. However, the bulk of data for ICRISAt Center remain un-processed. This deficiency, not limited to ICRISAT, extends to the very basic but important information on drop size distribution and intensity characteristics of SAT storms.

It is also evident from reviewing available information that a verification of soil loss dependence on rainfall erosivity indices is yet to be done. Whether EI 30 is indeed the best measure of erosivity in the SAT can be experimentally tested is such a way as to allow full monitoring of rainfall, runoff, and soil losses associated with individual storms. The effective index which emerges out of these verification studies should be the basis for constructing iso-erodent maps. It must be computed for periods that are sufficiently long so as to have statistical stability. Should continuously recorded rainfall data be unavailable, the index may be estimated from other rainfall records which are more easily available. The search for alternative indices should be greatly facilitated by ICRISAT's strength in compiling and analysing agroclimatic data for the SAT.

III. E.2. Soil erodibility -- Available literature reveals that the maximum K value published for any soil is 0.69; the minimum implying a completely non-erodible soil, is zero. The literature also shows that among the important SAT soils, Alfisols, Vertisols and Oxisols possess average K values of 0.4 or more, 0.3, and 0.1, respectively. No data is available for Entisols but vertic Inceptisols may be slightly less erodible than Vertisols. It is emphasized here, however, that much of this data is reported for temperate soils; experimental data for SAT soils of these orders are scarce. In any case, categorization of the soils at the order level of classification is clearly insufficient as a basis for quantitative planning. Due to ICRISAT's special emphasis on SAT Vertisols and Alfisols, the following paragraphs will summarize relevant information for these soils.

For Vertisols the susceptibility to runoff inducement and erosion is determined by:

> Shrinkage and swelling characteristics as
> primarily determined by water content and
> compaction history

- o Particle size distribution characteristics
- o Extent of self mulching, structural development, and aggregate stability
- o Sodic influences and subsequent infiltration and drainage restrictions

Under dryland agriculture, Vertisols are quite receptive to early wet season rainfall even when rather intense. Excessive runoff and erosion begin once the dry season cracks are closed and the water saturation deficit is diminished. Both are particularly pronounced in locations where drainage is slow due to limiting layers or spatial variability in physico-chemical characteristics. Because of their relatively high contents of active layer silicates (primarily, montmorillonite), Vertisols are quite responsive to structural modifications efforts. The timing of such efforts, e.g. tillage, however, is extremely critical to the quality of produced structural units for seed germination or root proliferation. The clear success of the broad-bed and furrow (BBF) design on Vertisols in the ICRISAT agro-zone arises becauses this design allows favorable structural, water storage and surface drainage in the soil (15, 20). Refinements in the design are required, however, to accomodate wide variations in soil properties or rainfall patterns at new localities or long term structural changes in existing ones. Such refinements may utilize manipulations in L, S, and/or P factors to quantitatively enhance maximum water storage with optimum surface drainage and tolerable erosion. However, manipulation of the K factor through structural modifications may also be necessary, e.g. international drainage and cracking patterns may be beneficially altered through amendment applications.

Alfisols, at least those cultivated in the SAT, are primarily characterized by the lack of structural development. Responsible for this are the combined contributions of deficient fine (clay-sized) particles particularly at the surface, inactivity of the prevailing clay minerals (kaolin), and, with prevailing cropping systems in SAT, the tendency to stabilize only minute amounts of decomposed organic matter within the soil mass. The increased clay content with depth (to form a characteristic argillic horizon) often distinguishes these soils from other "sandy" soils,(e.g. Entisols). On one hand, this increased clay content is not sufficient to induce stable structural formations; the content of < 2µm particles increases from 12% in the surface to 38% in the argillic horizon of the Patancheru series at ICRISAT Center (a 30% to 50% content of "active" clay is often presumed to impart favorable aggregation properties, 3, 23). On the other hand there is sufficient fine fraction to contribute to surface sealing and increased surface runoff when lower layers are mixed with surface layers in ridges and exposed in furrows by inverting type tillage operations (20). The enrichment of surface layers with coarse particles is assumed to be the result of clay migration with percolating water, termite activity, and/or selective erosion of fine particles. Fig. 7 shows one example of soil texture-structure relationships (23).

A major consequence of lacking or non-stable aggregation is the tendency of the soil to display rapid surface sealing following rainfall and crusting with subsequent drying cycles. This "crusting" often extends deeper than the immediate soil surface with the result being a consolidation of the soil profile (slumping) to a depth which is determined by several factors. It would appear, that the mineralogy and particle size distribution of many of these soils is such that easy slaking, maximum packing, and easy compaction are favored. The primarily kaolinitic mineralogy is reported to include varying quantities of 2:1 clays. The lack of success in managing these soils under rainfed conditions, particularly by use of ridges or BBF, may be explained by:

- Instability of surface structure and subsequent surface sealing and crusting which on one hand induce excessive runoff even early in the season and on the other hand directly effect seedling emergence.

- Possible localized droughts in the seed environment, e.g. in ridges or beds into which water entry is restricted by surface sealing.

- Weakness of installed land configurations, easy failure of ridges or beds, and excessive concentrations of induced runoff in the furrows which then undergo rilling and exaggerated erosion.

- Insufficient depth of the soil zone available for optimum root proliferation; this reflects mechanical impedence problems which are overcome only temporarily by tillage, and lacking water storage qualities as the soils generally are shallow and drain quite freely.

- Stoniness appears to be an occasional deterrent to effective land preparation.

It would appear that modifications in BBF or alternative systems should recognize these limitations of SAT Alfisols and should emphasize the structural build-up required to render long lasting tillage benefits. An optimization of the system as a whole should also recognize the importance of seepage capture for long term stability in the water supply for supplementary irrigation. Surface capture in tanks is generally inhibited by excessive seepage and its short term nature reduces its usefulness when it is really needed, i.e. during dry periods (77).

III. E.3. Topography and land management -- It would be safe to state that quantitative evaluations of slope steepness (S), slope length (L), and land shaping (P) factors in the SAT are meagre at best. It remains to be seen whether results of the many past experiments at ICRISAT Center for both Alfisols and Vertisols may be amenable to such evaluations. Among the availabile data, the effectiveness of tied ridging in West Africa (Alfisols?) is demonstrated by its assigned P value of 0.1-0.2, re-inforced ridges were assigned 0.1 (3, 21). Relatively recent experiments on ICRISAT Alfisols indicate likely residual beneficial effects from, "split strip", plowing (section IV. B.3.). Little data are available, however, on the systems's conservation effectiveness.

III. E.4. Cropping Systems -- Although values for the C factors for SAT cropping systems are generally lacking; good estimates may be possible by utilization of existing documentations of canopy characteristics, both for sole cropping and intercropping, littering and rooting habits, and residue management. The literature is quite rich with data on C values for such a wide variety of crops at such different agro-climatic zones that reliable values can be derived from similarities in crop morphology, growing habits, and annual rainfall erosivity distributions. For specific crops and combinations at ICRISAT Center, considerable historic watershed data have been collected and these may be utilizable for direct assessment of soil loss ratios and quantitative protective effects against erosion.

IV. GOAL AND OBJECTIVES

The goal of this sub-program is to maximize the productivity of land through reduced erosion and effective conservation of soil and water resources in the semi-arid tropics. Our objectives will be primarily to:

A. Quantify the rainfall erosion potential of major SAT soils based on inherent climatic, soil, and topographic characteristics.

B. Determine, quantitatively, the effectiveness of alternative land uses, cropping systems, and management practices in controlling the losses and maximizing the utilization of soil and water resources.

C. To integrate the above with other relevant information for use in developing optimum farming systems for the semi-arid tropics.

V. PROPOSED APPROACH AND RESEARCH PLAN

The above discussions indicate that a systematic research program of soil and water conservation should aim to provide two quantitative sets of data. The first is a baseline set which quantitatively defines the absolute potential of the inherent site characteristics to interact and determine erosion hazard. The second is a management set which defines, again quantitatively, the ability of alternative land management and cropping systems to modify the above hazard within an overall plan for optimizing the productivity of the farming system.

The question of scale arises at this point. Experiments which aim to determine absolute values for runoff and erosion, must be conducted at a scale which allows both processes to express themselves realistically as in the field situation. However, the scale should be small· enough to allow careful manipulation and analysis of necessary components. It would appear reasonable that the size of field plots for our studies should center around the unit plot of the USLE (22.1 m length with a width of 2 m or more). However, a combined evaluation of several components in integrated experiments will require larger plots or even small watersheds.

Some compromises in approach and scale may be possible during early evaluations of management options where relative, rather than absolute vaues are sought. For instance, rainfall simulation on very small plots (= 1 m 2 Fig. 5) looms as a very attractive method for examining such treatment effects as tillage, structural modification and mulching, or the role of seal or crust formations in determining the infiltration-runoff relationships. The savings in time and expense of using small plots can be considerable. In addition, sound experimental designs with sufficient statistical replications can be imposed to allow for spatial and temporal variability and the accurate assessment of treatment differences, a matter normally considered quite difficult on large field plots or watersheds. Ultimate verification of management effects, however, must be performed on a realistic field scale and in the presence of pertinent cropping variables.

V. A. Baseline Data for Assessing Erosion Potential

The purpose of this research will be to establish quantitative values for inherent site characteristics, namely rainfall erosivity, soil erodibility, and topography (slope-gradient and length) as causative and predictive erosion and control parameters. Two "master" sites have been designated, one each on an Alfisol and a Vertisol. Specific experimental conditions and data collection requirements are:

1. Continuous rainfall records with storm analysis capability down to 0.25 mm and 5 minute increments. Fortunately, while such records must be collected during the course of new experiments, historic data

may be available for long-term erosivity analysis at ICRISAT Center and elsewhere.

Soil preparation to maintain bare, cultivable, organic residue-free, and non-consolidated surface (fallow per USLE definition). Occasional super ficial tillage (such as roto-tilling twice a year) is required to meet these specifications. Soils at each site should be subjected to basic chemical, physical, and mineralogical characterization.

Site selection to allow plot location on uniform slopes with slope gradients and lengths lying within the relevant range for the specific site. Preferably, included gradients and lengths should bescattered aroun (the unitplot criteria of 9% and 22.1 meters, respectively. The deficiency in existing LS data for slopes under 3% makes it necessary that we, at ICRISAT, emphasize this range. Slopes of 0.4%, 0.8%, 1.6% and 3.2% as well as lengths of 12, 22, 33, and 44 m will be covered.

Laboratory facilities for gravimetric or turbidimetric determinations of sediment concentration in collected runoff.

Records should be compiled for a minimum of 5 years (20 years generally assures very improved stability in climatic pattern variations).

To proceed with collection of new data we have already installed inexpensive prototypes of runoff plots with which we had previous success in Hawaii. Details on the design of these plots are available elsewhere (6, 19, 24).

Data should be collected so that each storm or monitoring period will be represented by a rainfall total, continuous rainfall record, a runoff total or hydrograph, and a sediment concentration (preferably fractional) in collected runoff. Sediment concentration should be converted to soil loss per unit area. Rainfall erosivity analyis from recording raingage charts can be performed by a variety of methods. Most of these require computation of storm energy and maximum intensity for defined durations. While manual calculation of these values from recording rainfall charts is relatively simple, a computer-compatible digitizer would be necessary for processing large amounts of such data. Interrelationships among erosivity and soil loss for varying topographic conditions are the basis for determining valid rainfall erosivity indices, calculating soil erodibility, and establishing quantitative values for topographic parameters.

V. B. Management Alternatives

Within the USLE conceptual framework presented above, management options are intended primarily for manipulation of the crop cover (C) and land support practices (P) factors. The first would deal primarily with the attributes of various cropping systems and the second with the various land configurations. However, it must be recognized that many soils in the SAT have such poor structural and hydrologic properties that manipulation of the erodibility (K) factor may also be essential to overcome some serious limitations (e.g. cracking of Vertisols and crusting of Alfisols). Our intent, therefore, is to examine the roles of all three of these management options in maximizing conservation effectiveness and, therefore, productivity.

The experimental approach for testing management alternatives will utilize laboratory studies of soil structural modification, micro-plot studies of promising treatments using simulated rainfall, and intermediate scale studies on plots of similar design to those described above for collection of baseline parameters (standard USLE plots). The role of "watershed" scale research will depend on the extent to which design inputs from the above experiments are ready for adoption. Recommendations for technical refinements on operational scale watersheds will be the ultimate aim of these management studies. It would be prudent if these operational scale watersheds are managed as an integrated FSRP activity with continuous inputs from all subprograms as equal partners.

V. B.1. Vertisols -- By and large the BBF technology which is based on pre-monsoon cultivation and dry sowing to allow double-cropping, graded beds and furrows to improve micro-drainage in the seedbed and controlled macro disposal of excess runoff, improved verieties, fertilization, and crop protection is proving successful for dry-farming of these deep soils. However, continued long term evaluations of the technology and examination of alternative options based on experiences elsewhere are necessary as, already, there are difficulties which arise in specific (non-optimal) situations. Experiments should be designed to allow appropriate modifications of the technology for extension to new Vertisol situations, e.g. areas with substantially different rainfall characteristics or with unique preferences for certain cropping systems. ICRISAT's likely involvement in Sudan, is one such example.

Similarly, the wide differences among the physical properties of different Vertisols need to be taken into account for effective design of alternative land management systems. For instance, soils with poor structure or higher contents of clay-sized particles may require shorter furrow length (L) and more slope gradients (S) to allow for more effective surface drainage than the well structured or coarser textured soils. Amendment applications may be necessary to improve internal drainage. Changes in profile water storage in response to these modifications must be verified to insure the continued adequacy of water supplies for double cropping under BBF systems.

Even in areas that are ideally suited for direct use of existing BBF technology, there appear to be emerging problems which become pronounced only in the long term. The prominent tendency of these soils to crack may be an asset during the early part of the rainy season as cracks represent ready rainfall entry into the soil. Late in the season, however, these cracks appear to be detrimental to the growth of certain crops (whether by direct root damage or excessive water evaporation) and a deterrent to animal trafficability for post season land shaping operations. Cracking extent and pattern seem to related to compaction history, e.g. furrows appear to display more and wider cracks than beds or flat culture; the problem increases in older BBF systems. Fortunately, swelling and shrinkage are physical phenomena which are chemically sensitive. The contribution of even small amounts of exchangeable sodium (suspected by the relatively high pH particularly in lower horizons of these soils) to excessive swelling is well confirmed for montmorillonitic soils. This is particularly true with the slight electrolyte concentrations which prevail with rainfed agriculture. The likely benefits of calcium rich amendments to the structure of these soils, and subsequently the K factor, are well worth investigating. Mulching and organic residue incorporation should contribute to long term structural improvement.

Other than the above efforts, it is our intent to invest less research effort on the management of Vertisols than on Alfisols.

V. B.2. Alfisols -- Alfisols in the humid tropics appear to be more amenable to management for sustained agricultural productivity than those in the drier regions, e.g. the SAT. Much success has in fact been reported with minimum tillage, generous residue inputs (e.g. mulching) and, necessarily, heavy dependence on herbicide use within the cropping systems (16). Unfortunately, sustained vegetative activity and crop growth on SAT Alfisols is hampered primarily by the poor physical properties mentioned above, particularly the weak structure and meagre water storage in the profile. Modifying the land surface configuration and/or characteristics of portions of the root zone by conventional means appear to have only limited and short-term effects due to the extreme non-stability of soil structure. For instance, bunds, ridges, or beds fail quite readily when subjected to even moderate runoff events following rainstorms. Seals and crusts reform immediately following rains. It is doubted whether direct rainfall impact is even necessary for this to take place as the structural units are so weak that incipient failure may occur by mere wetting of the soil mass, e.g. from ponding or runoff. In a similar manner, a progressive consolidation of the root-zone is easily attained during dry periods which follow rainstorms, even when minimal external energy is imposed for compaction. Desiccation effects in the soil are the collective result of these phenomena which enhance high water losses by runoff and evaporation. In addition, the ultimate distribution of infiltrated water is often quite poor. For instance, the few centimeters of soil just below the surface crust or seal may undergo excessive drying as a result of high evaporation and suction gradients experienced by this soil zone. This worsens the overall poor water storage characteristics of the soil profile.

The proposed management studies on SAT Alfisols, therefore, will aim at manipulating the P, C, and K components as explained below. Supplemental irrigation studies are critical to the overall research strategy on these soils but will be discussed seperately in section V. C.

V. B.2.a. Primary tillage -- Aside from attempting to overcome crusting problems and optimize the configuration of the land surface for maximum runoff control, the creation of favorable soil zone for root profileration which remains stable over several seasons looms as an object of high priority for Alfisols. Several options present themselves in this connection, some are animal draft based, and others involve the use of mechanized tillage implements. The fact that N-mineralization has often been assumed a component of tillage benefits would require that N- fertilization become a deliberate part of the experimental design (SPC Link). This is particularly so where residue management is a variable.

Much research on primary tillage has been done during the past several years at ICRISAT, AICRPDA, and IRAT (West Africa). ICRISAT efforts have concentrated on tools designed to suit the BBF animal drawn implement carrier (Tropiculteur). A promising tillage technique to emerge with this is the "split strip" technique (13). This is a BBF system in which three passes are used to impose a more intensive tillage than standard plowing. The first is to split the bed, and the others to strip plow it throughout its full width. Among the apparent benefits attributed to this system are higher millet yields, and longer lasting effects than conventional tillage. However, with the very limited trials to date, it has not demonstrated clear-cut benefits over standard tillage and cultivation from the soil and water conservation view-point. We intend to closely examine this method for Alfisols when animal draft is the source of power for tillage.

A major limitation of animal drawn implements is the limited depth to which tillage is performed even with optimum soil moisture conditions (15 to 20 cm maximum). While it may be possible to provide a good quality seed-bed with such systems, this depth is inadequate for providing a sufficiently deep zone for optimal root proliferation in poorly structured soils. Serious consideration must be given, therefore, to experimentation with tools that are capable of effecting deeper and more intensive tillage. While this may appear to contradict the "small farmer" mandate, it is consistent with the CGAIR'S endorsement of the TAC's first priority objective of "ensuring adequate food supplies in the developing world". Should the optimization of production through mechanized tillage become viable technically on Alfisols, the potential for actual utilization of this technology on large scale will remain to be seen. It is relevant to indicate here that, in addition to the likely technical advantages of mechanized tillage, there exist clear timing advantages under dryland agriculutre where the competetive demands for various operations (plowing, planting, weeding, etc) peak together within the short time period which follows the early showers of the rainy season. For instance, the high power outputs may make it possible to introduce preseason plowing or allow faster achievement of . these operations should they start, as now, after the early rains of the season.

We propose to initiate experiments aimed at evaluating the comparative benefits of alternative intensive mechanized tillage methods to crop yields and runoff-soil loss relationships.

V. B.2.b. Soil structural modifications -- It would appear that generating a favorable soil structure which is stable over a full season or more is key to effective management of SAT Alfisols. Such cannot be achieved simply by crust breaking, intensive tillage or even surface mulching alone. In the short term, actual incorporation of organic or inorganic amendments which are effective in a direct reduction of water losses by runoff and evaporation as well as enhancing interparticle bonding and maintaining favorable and stable aggregation will be needed (modifying the K factor). A number of easily accessible and inexpensive inorganic industrial by-products loom as likely inputs to achieve rapid benefits to soils structure. Organic counterparts will be sought. Soil "conditioners", however, will not be emphasized as economic analyses have repeatedly shown them too costly for general agriculutral purposes.

In the long term, a farming systems' design which assures the maintenance of favorable structural conditions would be critical to the successful use of Alfisols. In the humid tropics, where these soils have more favorable structure, their organic matter contents are often in excess of 5%. The incorporation of beneficial organic matter from a sustained and reliable source within the cropping system would be the likely means of achieving favorable soil organic matter contents in the SAT. Commonly employed options in many farming systems include integrating a rapidly growing "green manure" and/or crop residue components in the cropping cycle.

The sources of organic matter for this purpose must be carefully investigated because of their apparent general scarcity in the cultivated areas of the SAT. This and the many competitive uses of crop residues may be deterrents to investigations of their value to soil structural improvement.

However, since the benefits associated with such improvement remain to be quantitatively demonstrated for Alfisols, such investigations should not be dismissed out of hand. The trade-offs between residue losses to fodder or fuel use and possible yield gains may not be so favorable in the short run but may be clearly beneficial in the long run.

Including, in the cropping cycle, plant species specifically intended for enrichment of soil organic matter appear to warrant strong consideration by FSR. As discussed earlier, rapidly growing tree species are prime candidates for this purpose. For maximum compatibility with "subsistence" cropping systems, leguminous species should be of advantage. For instance, certain species of Acacia and Leucaena are currently being promoted by "agro-foresters" as a means of meeting fodder, fuel, and "green manure" demands in many farming systems. In addition to nutrient cycling and improving soil structure, their benefits will extend to direct protection against loss and runoff control. Some non-legumes, e.g. Napior grass have been shown excellent performance when used in strip-cropping schemes for this purpose. The extent of these contributions will depend heavily on the extent and placement of the introduced species in the cropping systems. For instance, they may be strategically situated to protect field bunds against erosive runoff, to reduce water inundation of poorly drained areas, to act as wind-breaks, etc. A high degree of mixing of tree species with the usual annuals would also favor long-term improvements in the soil due to natural actions of roots and continuous inputs of litter, etc. Deep rooted species, therefore, should be preferred.

Another means of enhancing the C factor contribution is to modify existing cropping cycles so as to include cultivars with prolific vegetative production and root systems. Minimization of soil disturbance and, improved nutrient recycling may be a benefit of introducing herbicide usage whenever possible in the cropping cycle.

The short and long-term benefits of inorganic and organic amendments and the evaluation of alternative sources for both will receive a high priority in combination with our tillage investigations. Soil structural changes will be evaluated periodically by routine procedures.

V. B.2.c. Land surface configurations -- With the relatively mild topographies which characterize many SAT soils (generally < 6% slopes), drastic changes in land configuration e.g. by bench-terracing, are not generally necessary. Experiments have been conducted for many years at ICRISAT and AICRPDA to test a number of land configurations with occasional variations in tillage (15, 20). In contrast to deep Vertisols, where clear benefits were displayed by one configuration (namely the BBF system) over others, results on Alfisols are inconclusive and very much dependent on storm size and timing within the rainy season. Indeed BBF appears inferior to several other configuration (including the flat cultivation which is characteristic of traditional practices) whether for controlling runoff and soil losses or producing higher yields. Narrow bed (ridge) and wave bed and furrow systems fared no better. Among the trends which seem promising are likely benefits of contour bunding in which provisions are made for surface drainage of ponded water by special outlets in the lower slope, construction of ridges within bunded areas during the last intercultivation of the season, surface dust or organic muchling, intensive tillage, frequent and shallow cultivation, and tied ridging or furrow

Further experiments will be confined to the fewest treatments which have the most promise. Whichever treatments are selected, however, their influence should be determined in the long-term with view of the discussions in section V. B.2.b. Clearly, as for tillage, the stability of imposed land configurations require improved soil structural characteristics. These three aspects of management, therefore, will be fully integrated in our future investigations to optimize the physical soil conditions for crop growth.

V. B.2.d. Surface sealing and crusting -- Because seal and crust formations in Alfisols may be effective inhibitors to seedling emergence and inducers of runoff from many storms, seeding on the sides of the ridges which are less prone to crusting may be beneficial. Furthermore, where the crop allows, furrow planting to utilize the water shedded from (sealed) beds or ridges more effectively may be a viable alternative. The soil zone right under the furrow will likely have more favorable water content and less cursting so as to insure better seedling emergence and early stand establishment. This would be re-enforced by the fact that progressive enrichment of sand-size particles in this zone is likely as runoff moving down slope removes only fine particles with it. Stand establishment in the furrows should contribute the added benefits of reducing runoff and erosion. The good permeability characteristics of Alfisols would likely disallow localized drainage problems in the furrow zone as would be feared in heavier soils where raised bed or ridge planting is of definite advantage. In addition, it is expected that amendment treatments as proposed above (V. B.2.b.) will reduce crusting problems and enhance free drainage in selected field portions. This will be subjected to quantitative evaluation.

V. B.2.e. Water supply for supplemental irrigation -- A major feature of Alfisol management must be to satisfy their requirement for supplemental irrigation. The need to continue harnessing and storage of runoff water is obvious. Low cost sealing techniques for storage tanks are yet to be developed. On border-line rainfall situations which appear to prevail in drier regions where some Alfisols (and Entisols) prevail (e.g. Botswana, West Africa), effective methods for runoff inducement from designated catchments for storage and use on limited land areas is a subject of increasing importance. PSRP may wish to engage in preliminary experiments to develop needed expertise in this area. To allow maximum benefits through the optimization of the ratio of catchment to receiver areas, runoff modelling efforts which emphasize the effects of alternative land management practices must be intensified.

A major point of emphasis when considering water supplies for Alfisols is the need to increase research efforts on the potential for sustained use of underground water resources. This water source is important, and in fact occasionally utilized at present. However, its importance will be further increased should soil manipulation intended to minimize runoff and therefore enhance deep percolation . be successful. Since Alfisols' profile capacity for water storage is limited, water moving beyond the root zone is lost to the crop unless it can be captured for reuse in supplemental irrigation. Simplified techniques are needed for delineating underground water recharge patterns, establishing the importance of percolation or ponding tanks, defining lag-time with respect to rainfall events, and predicting the stability of supply within the year for the prevailing patterns of rainfall. There may also be occasional questions of water quality for irrigation where salt intrusion represents a hazard. The Economics Program has been actively engaged in an inventory of a large watershed near Aurepalle and PSRP needs to start counterpart investigations to tackle these water supply questions as an integral part of overall watershed optimization efforts. Even with effective tank sealants, doubts are always cast on the reliability of surface water supply available for storage during drought periods in most year (22, 26). Therefore, it remains to be seen whether there is longer term stability in the water supply from underground sources.

V. C. Optimized Management of Supplemental Irrigation Water

Striking benefits have been reported from even a few number of irrigations, alternatively called life-saving or crop-saving, for both Vertisols and Alfisols at ICRISAT and elsewhere (15). Unfortunately, in most SAT areas of concern, the supply of water which is normally available for use in irrigation is very limited. Therefore, maximization of benefits from supplemental irrigation is an important priority for complementing the effective control of rainfall-runoff relationships through improved land and soil management practices. Such maximization must be achieved through increased water use efficiency by the combined control of the timing, quantity, and method of irrigation. Most of the ICRISAT is this area has been on supplementary irrigation during the post-rainy season. Critical drought periods are occasionally encountered during the rainy season as well, particularly on Alfisols. Supplemental Irrigation during these periods can have remarkable benefits as well. Information available from drought stress physiologists will assist in determining critical growth stages for beneficial timing of water application. The applied quantity should depend on soil water status and available supplemental supply. Selection of the proper application method is the major factor determining the use efficiency of a given quantity of water. concepts for SAT areas with limited irrigation water supplies have emerged in recent years (3, 26).

For both Vertisols and Alfisols, optimization experiments based on the Limited-Irrigation-Dryland (LID) system will be tested. This system utilises reductions in planting density down the slope of furrow shaped fields, in the presence or absence of furrow dams (tied ridging), to eliminate or minimize runoff and automatically maximize the benefits of applied irrigation water in both wet and dry years (26). Water may be applied in alternate or all furrows at rates which are determined to control its advance down the furrows as desired; the emerging SURGE modification is an example of such control.

We propose to initiate experiments along this concept to increase the use efficiency of supplemental irrigation water in conjuctive irrigated - dryland systems. In addition to manipulation of planting density, other modifications of this system may be amenable for ICRISAT's cropping systems. Examples are intercropping combinations which include shallow-rooted crops near the furrow and deep-rooted ones far, (LID is currently used on single crops, mostly sorghum) or planting crops with different water requirements on the upper (conventionally irrigated), middle (tail water runoff), and lower (dry land), sections of the furrows.

V. D. Salinity and Sodicity Problems

There appears to be an increasing need to develop a means of rapid quantitative assessment of saline, sodic, and/or water logging conditions and their effects in locations of prime concern to ICRISAT. This is particularly true where supplemental irrigation is practiced using water of marginal quality. Also a number of researchers in the crop improvement programs are interested in one aspect or another of crop tolerances to salinity or sodicity.

It would appear that adaptation of the four-electrode earth resistivity technique for use in SAT soils is of strategic importance. This technique, with horizontal Wenner arrays or in probe configurations is capable of providing a direct measure of bulk soil salinity, water table level and, when used periodically, subsurface water and salt seepage patterns.

Sodic conditions may be encountered and can exert pronounced effects on SAT soils and crops even at low levels of exchangeable sodium percentage (ESP). This is due to the fact that frequent effective flushing of salts by rainfall results in very low soluble salt concentrations in soil solution where agricultural systems are primarily rain-fed. Sodium damage to soil structure and "toxicity" to plants are most pronounced at low overall salinity levels; ESP values of 5 or less can exert such deterimental influences, particularly in structurally sensitive soils such as Vertisols. Fortunately, remedial actions by use of soil amendments are more feasible economically the lower the ESP. The need for and benefits of amendment application will be determined jointly with the studies indicated in SectionV. B.2.b.

VI. COOPERATIVE AND SERVICE ACTIVITIES

The distinction between cooperative and service activities in our context will be based on whether an experiment is conducted within the framework of a jointly planned project or as a routine determination within the framework of a project which is planned independently. Both activities are vitally important for ICRISAT. However, in view of the often urgent nature and massive workload associated with service activities, it would be wise to accept these as an Institute- or Program-wide responsibility.

VI. A. Cooperative Research

Within the conceptual framework presented above as a proposed basis for research in the sub-program, we foresee engaging in the following cooperative research:

- Cooperative research with other FSRP sub-programs to verify the USLE components of common interest. Specifically, joint work with agroclimatology, cropping systems, farm power and equipmenbt will be important for quantifying the rainfall erosivity, crop canopy and residue factors, and the land shaping practices components, respectively. Optimistically, many of the records already existing with these sections will be amenable for this analysis thus providing a solid set of historic data which will lend credence to any data to be collected from new experiments. An added advantage for climatic data in particular, is that much of the analysis can cover SAT areas beyond ICRISAT center, particularly in Africa. The strength acquired by agroclimatology in rainfall probability analysis will be a direct asset in this analysis. All research involving amendment evaluations will be coordinated with the soil chemistry and fertility sub-program to ensure that observed crop responses are deliberately interpreted from both physical and nutritional view-points.

- Cooperation with other FSRP subprograms in adaptive research, both on operational scale watersheds and on farm. It is proposed, however, that such activities collectively, be a program responsibility with rotating coordinators from different subprograms. The demonstrational value of operational scale watersheds and the need for these to provide the direct link with on-farm work justify such a manner of operation.

- Cooperation with national programs for sharing relevant research experience and extending mutually agreeable management experiments to sites with various Alfisols. This will allow a deliberate assessment of management parameters on a spectrum of such soils so as to ensure adequate representation of important (benchmark) Alfisols.
- Cooperation with those ICRISAT sub-programs with interst in crop modelling to assist with improved quantitative assessments of soil water status and structural characteristics of the root zone in relation to crop response.

VI. B. Service Functions

Just as much of the research conducted around ICRISAT requires proper monitoring of soil fertility and chemistry in experimental sites, so there is frequent need for monitoring soil physical properties. Most demand of this nature has been for the determination of water content, for which neutron scattering is now shown reliable for ICRISAT soils. Other assessments include changes in soil compaction, crusting properties, and occasional needs to identify the location of and depth to water tables. Indeed, it would appear necessary that an updated inventory of important soil physical characteristics for ICRISAT fields, including depth and particle size distribution, is much needed. We propose the expansion of FSRP's soil chemistry and fertility services by adding a physics counterpart. A first class laboratory which is continuously in a position to provide water retention data, field soil-water measurements particle and aggregate size and stability characteristics, and other routine service (even conducting occasional laboratory scale experiments) is a must. Leadership and staffing of such a facility must be decided realistically to allow taking full advantage of it. Should the activities of the facility be overseen by a pool of scientists, this pool would also engage in experimental design and data interpretation for the benefit of those for whom the data is required.

Centralization of these services will also assist in efficient data gathering, handling, storage, and processing by, economically taking full advantage of recent computer-compatible instrumentation.

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Table 1: Erodibility of representative Alfisols (A), Vertisols (B) and Associated Soils

(Source: 7)

Series or Identification*	Type	Location	K Value	Source
Dunkirk	silty loam	Geneva, NY	0.69	Wischmeier & Smith 1978
Dayton		Oregon	0.54	Roth et al. 1974
St. Clair	subsoil	Michigan	0.48	Roth et al. 1974
Keene	silty loam	Zanesville, OH	0.48	Wischmeier & Smith 1978
McGary	subsoil	Indiana	0.36	Roth et al. 1974
Kawaihae	rocky silty loam	Hawaii	0.35	Dangler & El-Swaify 1976
Rabat		Morocco	0.35	Heusch 1970
Hagerstown	silty clay loam	Pennsylvania	0.31	Wischmeier & Smith 1978
Putat		Indonesia	0.26	Bols 1978
Gampela	Ferruginous	Upper Volta	0.25	Roose 1977b
Saria	Ferruginous	Upper Volta	0.25	Roose 1977b
Seta	Ferruginous	Senegal	0.25	Roose 1977b
Puñang		Indonesia	0.14	Bols 1978

*Identification provided when series was not named.

(A)

Series or Identification*	Type	Location	K Value	Source
Mayberry	subsoil	Nebraska	0.67	Roth et al. 1974
Pawnee	subsoil	Nebraska	0.45	Roth et al. 1974
Shelby	loam	Missouri	0.41	Wischmeier & Smith 1978
Marshall	silty loam	Iowa	0.33	Wischmeier & Smith 1978
Lualualei	clay	Hawaii	0.30	Dangler & El-Swaify 1976
Austin	clay	Texas	0.29	Wischmeier & Smith 1978
Jegu		Java	0.20	Bols 1978
Portageville		Missouri	0.05	Roth et al. 1974

*Identification provided series was not named.

(B)

Table 2: Analytical data from some eroded and noneroded soils (probably Oxisols) in Tanzania (Source: 7)

Depth (cm)	Clay (%)	Silt (%)	Sand (%)	pH	C (%)	P (ppm)	Exchangeable cations					C.E.C.	Bases (%)	Zn (ppm)	Cu (ppm)
							Ca	Mg	K (meq./100 g)	Na	H				
Profile D 1 (eroded plot)															
0-15	26.6	3.1	70.3	4.51	1.40	6	1.37	0.95	0.15	0.10	12.2	14.8	17.6	1.0	5.7
15-30	27.3	4.2	68.5	4.59	1.34	<2	2.08	1.16	0.11	0.06	11.3	14.7	23.1	0.9	4.1
30-60	34.2	3.0	62.8	4.50	--	<2	1.50	0.70	0.10	0.06	11.8	14.2	16.9	1.1	3.5
60-90	37.4	2.6	60.0	4.48	--	<2	1.21	0.48	0.09	0.05	11.9	13.5	11.9	1.0	3.3
90-150	38.6	2.3	59.1	4.46	--	<2	0.79	0.20	0.14	0.18	12.4	13.7	9.5	0.9	3.3
Profile D 2 (noneroded plot)															
0-15	21.1	3.5	75.4	5.29	2.59	33	5.21	2.05	0.32	0.16	8.3	16.0	51.4	3.5	31.0
15-30	21.7	4.2	74.1	4.78	1.22	5	2.28	1.79	0.18	0.18	8.4	12.8	34.6	0.9	4.4
30-60	21.4	3.5	75.1	4.49	0.98	3	1.76	1.32	0.19	0.22	8.1	11.5	30.2	1.9	4.2
60-90	24.9	4.1	71.0	4.29	0.53	3	1.20	0.58	0.14	0.12	6.6	8.6	23.6	5.5	8.2
90-150	30.6	2.3	67.1	4.51	0.49	<2	1.63	0.44	0.10	0.06	6.7	8.9	25.1	1.6	2.9
Profile D 5 (eroded plot)															
0-15	49.5	25.8	24.7	4.07	1.90	5	2.32	1.36	0.19	0.04	21.7	25.6	15.3	0.7	3.3
15-30	55.5	25.6	18.9	3.80	1.31	<2	0.77	0.25	0.16	0.03	24.7	25.9	4.7	0.8	2.3
30-60	63.8	19.6	16.6	3.88	--	<2	0.69	0.07	0.16	0.03	26.6	27.6	3.4	0.6	2.2
60-90	63.2	18.8	18.0	3.82	--	<2	0.54	0.07	0.15	0.03	29.6	30.4	2.6	0.5	2.3
90-150	60.9	21.5	17.6	3.81	--	<2	0.32	0.06	0.12	0.04	24.4	24.9	2.2	1.5	2.5
Profile Ka II, IA (virgin land)															
0-15	39.1	25.2	35.7	5.15	2.52	12	6.11	4.04	0.18	0.09	15.5	25.9	40.2	3.3	3.3
15-30	57.2	23.4	19.4	4.17	1.45	3	2.20	0.82	0.10	0.07	21.7	24.9	12.8	0.8	2.5
30-60	64.0	20.8	15.2	4.10	--	4	1.40	0.48	0.10	0.07	25.7	27.8	7.4	0.6	2.4
60-90	60.1	22.0	17.9	4.12	--	3	1.80	0.98	0.11	0.08	21.7	24.7	12.0	1.1	3.1
90-150	65.7	19.0	15.3	4.15	1.11	5	1.52	0.80	0.11	0.08	20.6	23.1	10.9	0.8	3.3

Table 3: Productivity benefits of improved conservation practices on deep Vertisols during 1976-1977 at ICRISAT Center watersheds

(Source: 15, modified)

Watershed No.	Practice/Slope	Intercropping			Sequential cropping		
		Yield kg/ha		Gross value Rs/ha	yield kg/ha		Gross value Rs/ha
		Maize	P.pea		Maize	C.pea	
BW1	Bed/0.6 %	3260	720	4870	3310	600	3840
BW2	Bed/0.6 %	2910	900	4960	3090	450	3410
BW3A	Bed/0.4 %	3590	670	4930	2970	760	3800
Mean		3290	760	4920	3120	600	3680
BW3B	Flat	3030	620	4470	2350	440	2750
BW4B	Flat	2790	560	3940	2930	280	3000
Mean		2910	620	4210	2640	360	2870

Table 4: Selected characteristics of a deep Vertisol at ICRISAT Center. (Source: 20)

Depth (cm)	Particle size distribution % of total				Moisture holding capacity (%)		Bulk density (g/cm^3)
	clay (.002 <mm)	silt (.05-.002 mm)	sand (2-.05 mm)	coarse fragments >2 mm	1/3 bar	15 bar	
0-15	51.7	20.8	21.5	6	31.0	19.5	1.20
15-30	53.9	20.5	19.6	6	32.2	19.7	1.30
30-60	55.5	19.8	18.7	6	33.5	20.2	1.40
60-90	58.0	20.1	15.9	6	34.4	20.0	1.40
90-120	61.2	20.0	11.8	7	34.3	20.0	1.42

Table 5: Selected characteristics of an Alfisol at ICRISAT Center. (Source: 20)

Depth (cm)	Particle size distribution % of total				Moisture holding capacity (%)		Bulk density (g/cm^3)
	clay (.002 < mm)	silt (.05-.002 mm)	sand (2-.05 mm)	coarse fragments >2 mm	1/3 bar	15 bar	
0-15	13.2	6.1	75.7	5.0	11.2	4.4	1.50
15-30	22.3	9.7	63.0	6.0	14.6	7.2	1.58
30-60	31.1	9.0	51.9	8.0	15.0	8.1	1.59
60-90	38.3	8.8	41.9	12.0	14.8	8.2	1.46

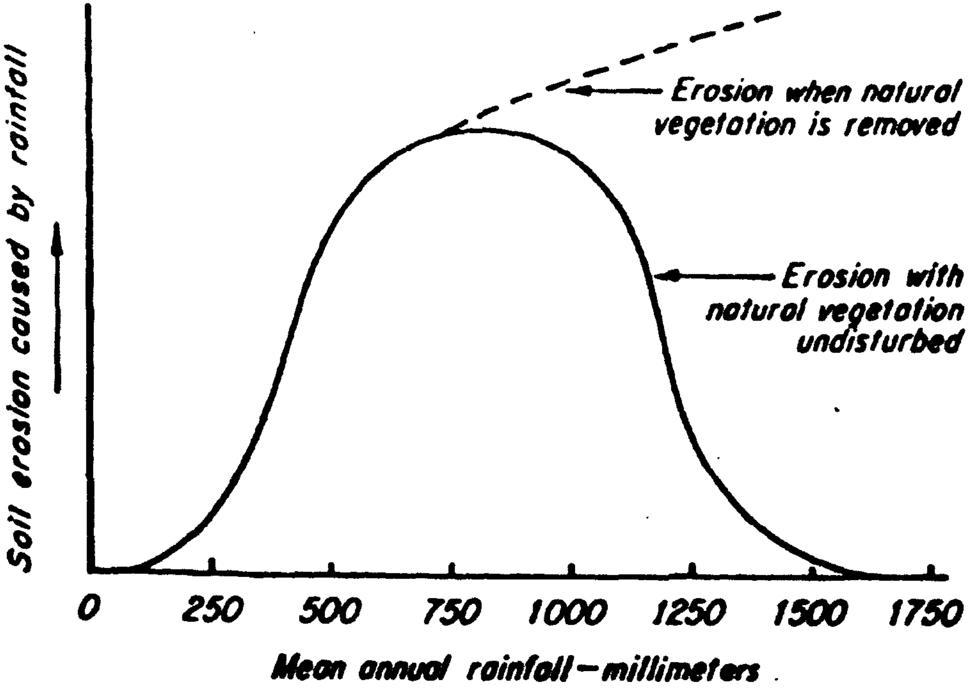

Fig. I : CHANGES IN SOIL EROSION TRENDS WITH RAINFALL (Source: 12)

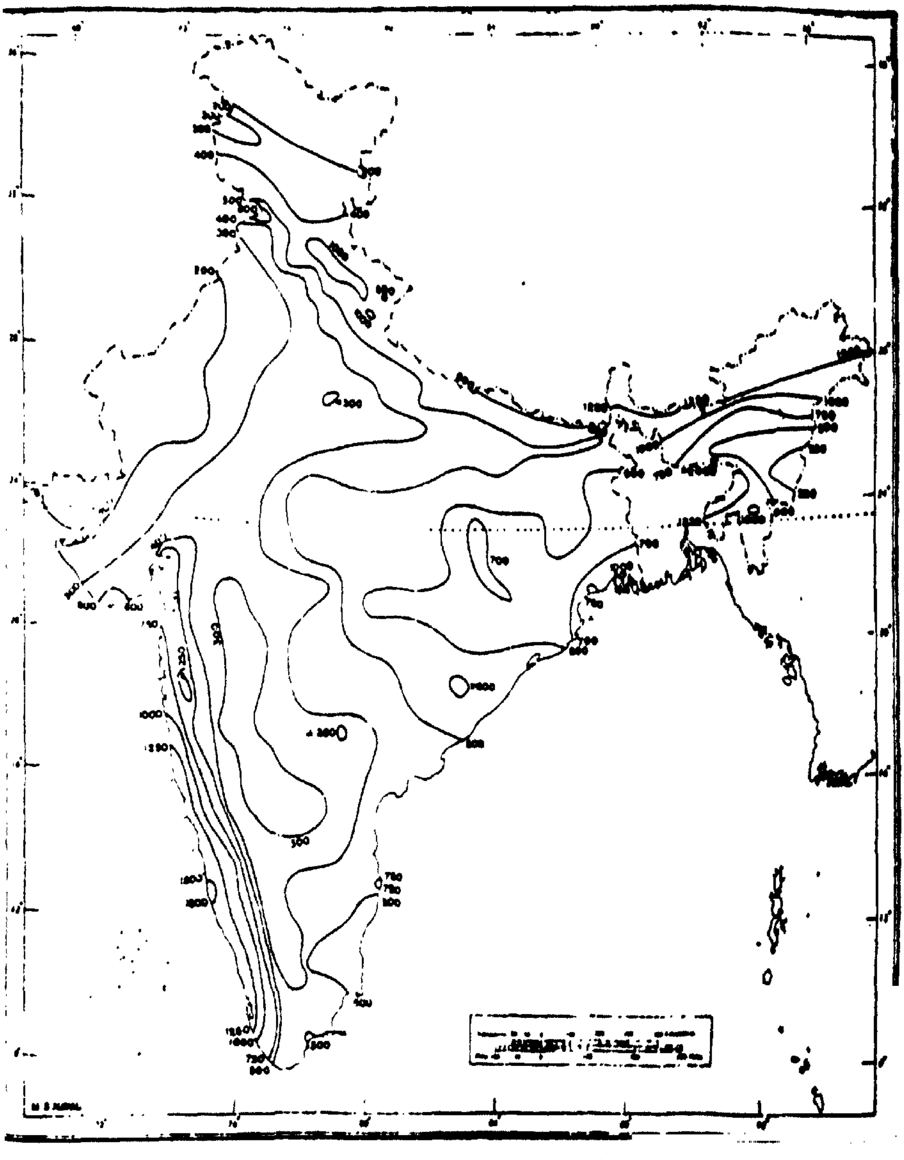

Fig. 2 : TENTATIVE ISO-ERODENT MAP OF INDIA (Source: 2)

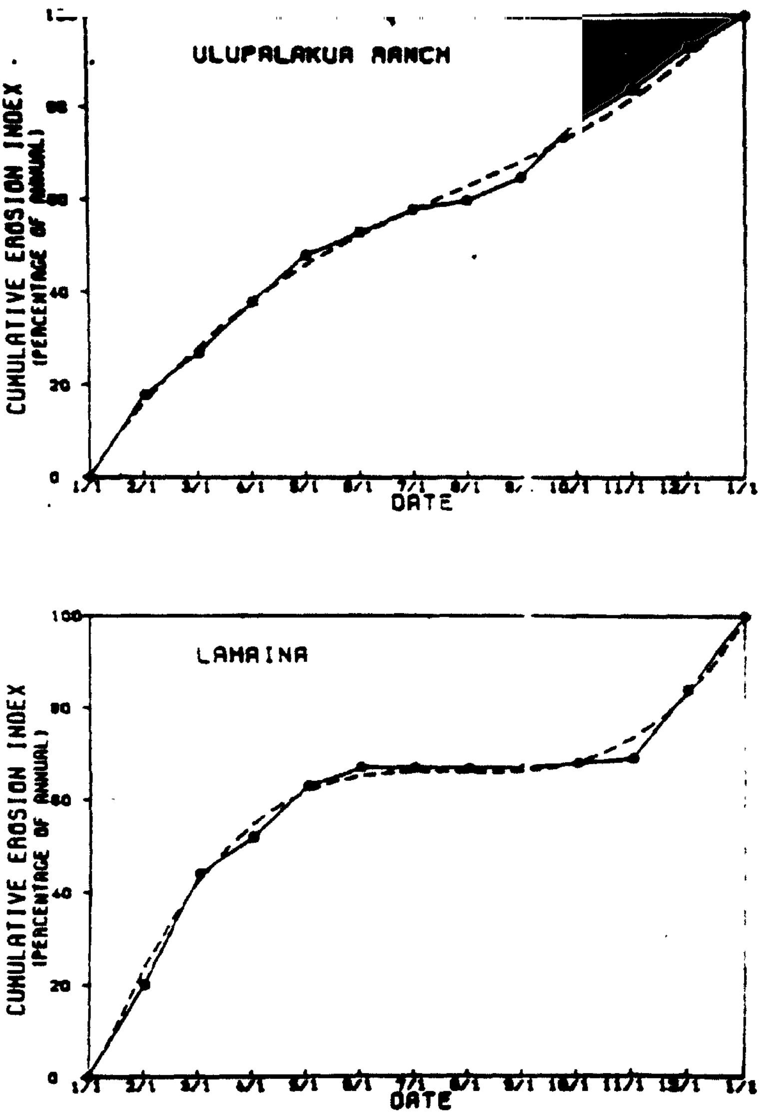

Fig. 3: MONTHLY EROSIVITY (EI_{30}) DISTRIBUTION CURVES FOR TWO LOCATIONS IN HAWAII (Source: 18)

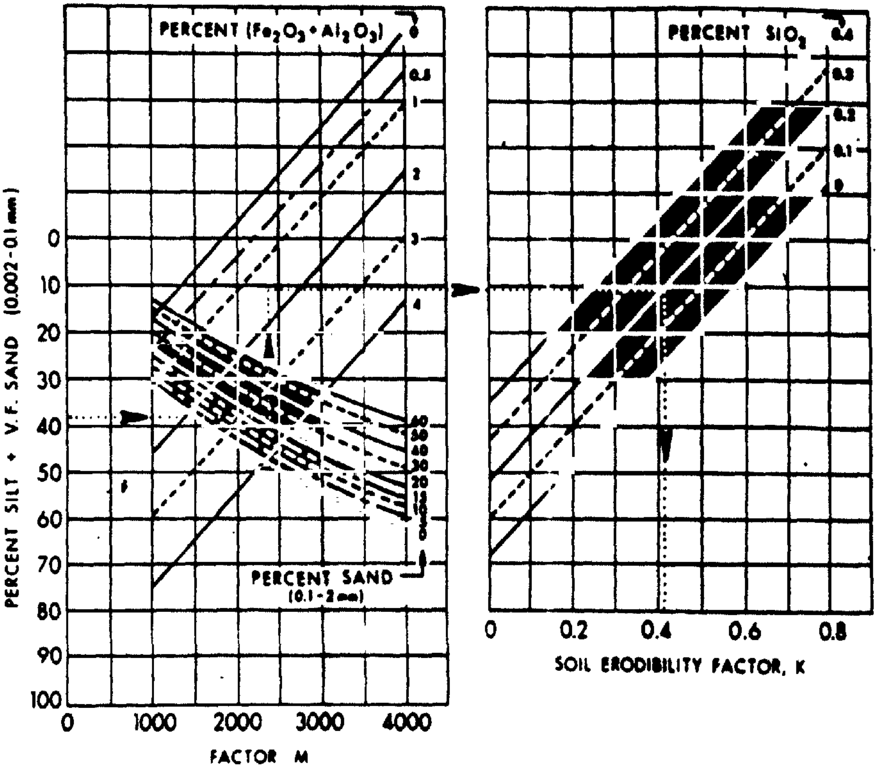

Fig. 4: ROTH, NELSON, AND ROMKENS' (1974) NOMOGRAPH FOR SOIL ERODIBILITY ESTIMATION. (Source: 7)

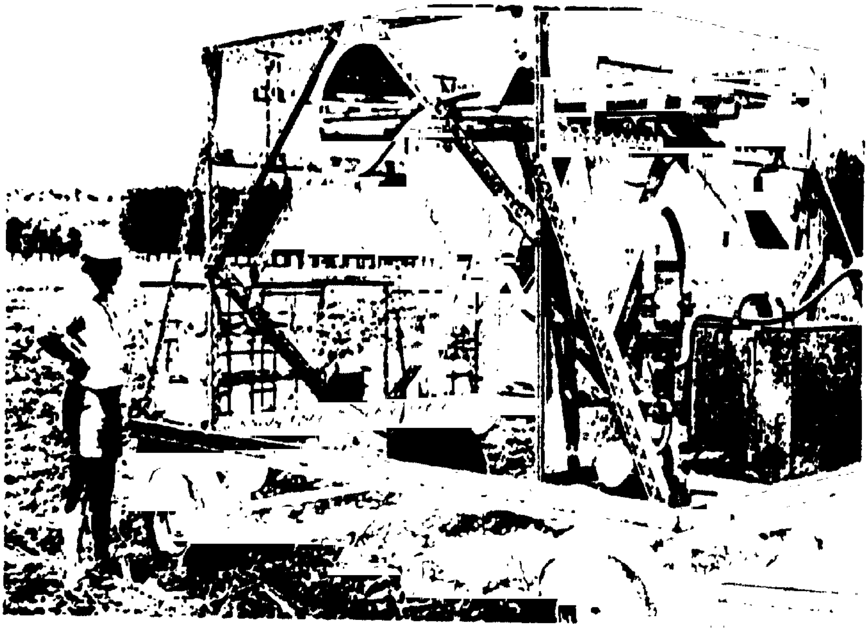

Fig. 5: RAINFALL SIMULATOR FOR CONTROLLED SOIL EROSION AND RUNOFF STUDIES.
(Source: 11)

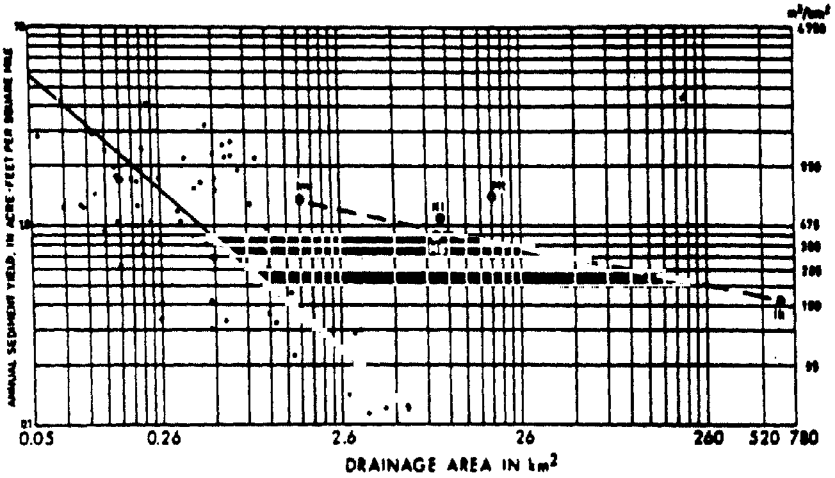

Fig. 6: RELATION OF MEAN ANNUAL SEDIMENT YIELD TO DRAINAGE AREA FOR THE FIVE CATCHMENT BASINS IN TANZANIA (OPEN CIRCLES) COMPARED TO SEVENTY-THREE SEMIARID BASINS (DOTS) IN EASTERN WYOMING, U.S.A. Ik = IKOWA WATERSHED; Im = IMAGI WATERSHED; Kl = KISONGO WATERSHED; Ms = MSALATU WATERSHED; Mt = MATUMBULU WATERSHED. (Source: 7)

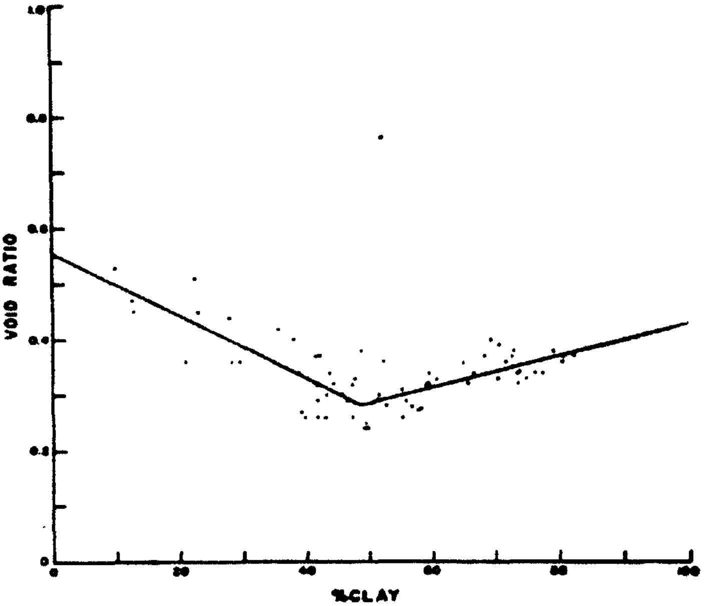

Fig. 7 : EFFECT OF CLAY (< 2 μm) PERCENTAGE ON AGGREGATION AS INDICATED BY THE VOID RATIO OF BLENDED SOIL AGGREGATES (Source :23)