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Factors affecting soil erosion hazards and conservation needs for tropical steeplands [1]

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Abstract

Understanding the basic processes and factors that are responsible for inducing land degradation, particularly soil erosion and associated phenomena is critical to the conceptualization, design, and implementation of productive, stable, and sustainable agricultural systems. This is particularly so on steeplands where the potential for soil erosion and runoff water losses is high. The productivity and degradation hazards on these lands are determined by the site's climate, soil and topography. However, their uniqueness lies more with their topographic constraints than with other factors. Use of steeplands is an increasingly common situation in the tropics because of high population pressures and continuing encroachment on hilly lands. Erosion potential and actual erosion in these settings may exceed tens or even hundreds of tons of soil loss per hectare per year; thus the selection and design of cropping systems, land management systems, and water management systems must be tailored to attain effective runoff and erosion control in order to avoid their detrimental impacts both on-site and off-site. Contrary to the customary arguments for the 'long-term' nature of erosion impacts; enhancing the conservation-effectiveness of rainfed farming on tropical steeplands can be shown to provide both short- and long-term benefits to the farming system, the overall economy, and the environment. Productivity-enhancing crop and soil and water conservation management approaches (biological measures) may be more important than structural measures in imparting long-term sustainability. Incorporating indigenous knowledge into project design should be emphasized to assure the farmer's involvement and cooperation in planning, implementing, and maintaining conservation measures.

Keywords: Runoff; Soil loss; Topography; Rainfall; Tropical soils; Tillage systems; Empirical models; Cropping systems; Tillage systems; Land-use systems; Rainfed farming; Socio-economic factors; Conservation policy

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1. Introduction

The characteristics of and management practices employed at a given site combine to determine the extent and rates of runoff and erosion from agricultural lands. Climate, soil, and topographic characteristics determine runoff and erosion potential. Empirical and process models are available for quantifying the contribution of erosion–inducing factors and predicting or controlling soil loss. Unfortunately, neither the inherent factors nor the influence of prevailing land use systems (e.g. crops) are well understood for tropical steeplands where topography represents a constraint to agricultural productivity and the most critical promoter of degradation. Most 'available' models are empirically derived and designed for temperate, 'conventional' (mildly sloping) crop lands. The vast majority of data for steep slopes are extrapolations. Furthermore, surface erosion, the object of most modeling efforts, is often less important than gullying or mass erosion in steeplands. The current state-of-the-art for predicting and controlling these phenomena is extremely young at best. The lack of reliable quantitative tools for predicting and controlling runoff and erosion has often led to the adoption of imported, untested, technologies and remains the strongest technical limitation for prescribing effective conservation practices on harsh landscapes.

Slope steepness represents probably the single most formidable technical obstacle to the effective cropping of mountainous areas in the tropics. Steeplands prevail in the highlands and uplands where moist forests are the natural vegetation and are essential contributors to the stability and sustainability of watershed ecosystems. When conservation-ineffective agricultural uses are introduced in such lands, they often produce ecosystem instability and detrimental impacts both on-site (erosion and deterioration of catchment quality) and downstream (flooding, sedimentation, and deterioration of water quality). Therefore, no where is the quantitative understanding of erosion processes and conservation needs more important than for steep lands.

While there is no universal definition for 'steep lands', slopes of lands accepted as potentially usable for unlimited agricultural development normally lie below 15 to 20%. Land suitability classifications differ in how they incorporate land qualities into qualitative or quantitative schemes. Slope steepness, nevertheless, is invariably included as a 'quality' in so far as it determines accessibility, trafficability, resistance to erosion, flooding hazard, and potential for mechanization. Managing all these aspects for stable agricultural development may require substantial economic inputs as determined by the characteristics of the terrain and the ability of the land user.

This paper will discuss the state-of-the-art for the prediction of erosion from and formulation of effective conservation measures for steep lands in the tropics. Because slope characteristics are the primary land-use constraint and least understood erosion promoter, an effort will be made to highlight available information and research needs on this aspect.

2. The setting

Aside from their distinctive, diverse and harsh topographic characteristics, steeplands in the tropics are normally also characterized by high rainfall (udic moisture regime), dense forest vegetation in the natural state, and diverse but predictable soil associations along various segments of the landscape.

Prevailing soils are the Oxisols, Ultisols, or Inceptisols; the first dominate in less steep locations and give way to the latter as the slopes increase. In volcanic ash rich areas, Andisols (Andepts) dominate the landscape. In all soils leaching is excessive and nutrient loss from soils is accelerated when the nutrient-cycling forest vegetation is removed. Prevailing minerals in these highly weathered soils are usually of low activity and generally display low ability to retain sorbed nutrients against leaching. Depending on the location and erosion history, the soils may also be very shallow and physically restrictive to crop growth, particularly in eroded Ultisols. Soil loss tolerances, because of these factors, must be set at considerably lower values than for soils in the temperate zone.

The primary cause of degradation in these locations is population expansion and increasing encroachment on such marginal lands. Shifting cultivation systems are changing to shorter, or absent, fallow periods with detrimental impacts to ecosystem stability. In addition, since such areas generally represent upper catchments or watersheds in basins of major rivers, there are well documented off-site impacts of that instability on downstream land users and investments such as water storage and hydro-electric power generation structures. Gullying and mass-wasting are abundant forms of erosion in these settings, both can prevail even in the absence of human disturbance.

3. Quantifying topographic effects on soil erosion from steeplands

Determination of how slope length and steepness influence soil erosion from steep lands has long been a source of frustration and concern for scientists as well as practitioners in action agencies. Data on the effect of slope length and steepness under natural precipitation are rare for slopes above 16%. This is understandable since lands in Western societies have been seldom cultivated on such slopes. Research plots located there would be costly to install and maintain, and the quality of data is difficult to ascertain because of remoteness, difficult access, and extremely variable landscapes and natural events. Qualitative surveys and observations are often useful but do not provide adequate data for establishing predictive relationships. The lack of reliable predictions looms as the strongest technical limitation for prescribing effective conservation practices on harsh landscapes.

El-Swaify et al. (1987) reviewed the progress of predictive models in quantifying the effects of slope characteristics on erosion. Renner (1936) was one of the first to study (using field surveys) the effects of slope steepness, aspect, soil, vegetation type and density, and accessibility to livestock on erosion from rangelands within the Boise River watersheds. Horton (1945) developed a relationship between shearing forces on the soil surface and slope length and steepness for overland flow. He did not discuss length of slope in his study. His data reveal, however, that soil loss per unit area varies directly with the shearing force and thus with slope length to the 0.6 power. Packer (1951) used rainfall simulation on an ungrazed portion of the Boise River watershed with slope steepness from 33 to 66% and noted that slope steepness had no significant effect on runoff or erosion. The shortness of his plots was mentioned as a possible reason, because there was no opportunity for runoff to concentrate or rills to develop and thus express the erosion process realistically.

Some of the most comprehensive evaluations for cropland were made by Zingg (1940). He analyzed simulated rainfall data on contrasting soils used by earlier workers and recommended the relationship:

$$A \propto 0.6 s^{1.4} \quad (1)$$

where A = average soil loss per unit area and s = percent slope ($s = 100 \tan\theta$, where θ = slope angle in degrees). Musgrave (1947) suggested a different general equation for slope steepness effect on erosion:

$$A = a + b s^{n} \quad (2)$$

where a, b, n are constants influenced by rainfall intensity, soil, and land cover. By 1957, considerable soil loss data were available from several cropland locations. Smith and Wischmeier (1957) used a parabolic equation to fit these data, those from Zingg's rainfall simulator tests, and from studies at Dixon Springs, IL, and Zanesville, OH, into an empirical model. The recommended relationship was:

$$A \propto 0.43 + 0.30 s + 0.043 s^{2} \quad (3)$$

Smith and Wischmeier (1957) also analyzed length of slope data for 136 location years at ten sites under corn and cotton. The data best fit the form:

$$A \propto x^{m} \quad (4)$$

where x is the slope length and m is the fitted exponential constant. Average values for m ranged from 0 to 0.9, with a location-weighted average of 0.46. In formulating the universal soil loss equation (USLE), Wischmeier and Smith (1965) combined Eqs. (3) and (4) in the following slope length and steepness relationship:

$$A \propto x^{0.5}(0.43 + 0.30 s + 0.043 s^{2}) \quad (5)$$

This equation was the basis for computing the LS factor of the USLE and is not valid for slopes less than 3%, greater than 18%, or longer than 122 m; the values provided by the authors for these conditions are only approximate extrapolations. Later, after noting increased use of the USLE on steeper slopes of rangelands, forest lands, mine spoil areas, and construction sites, Wischmeier and Smith (1978) modified Eq. (5) as follows to reduce steepness influence on predicted soil loss:

$$LS = (x/22.1)^{m}(65.41 \sin^{2}\theta + 4.56 \sin\theta + 0.065) \quad (6)$$

where LS is the dimensionless slope length and steepness factor relative to a 22.1 m slope length of uniform 9% (or $\theta = 5.1°$) slope, and $m = 0.5$ if slope is 5% or more, 0.4 on slopes of 3.5 to 4.5%, 0.3 on slopes of 1 to 3%, and 0.2 on uniform slopes of less than 1%. The major difference between Eqs. (5) and (6) was a change from the tangent to the sine of slope angle. This change is consistent with expected physical manifestation of the erosivity of runoff as it moves down slope, which is a direct consequence of the shear force exerted by overland flow on its boundary with the soil matrix. Mathematically, predicted soil loss values based on the sine and tangent of the slope angle would be nearly equal on slopes less than about 20%. Above 20%, the tangent of slope angle increases rapidly and approaches infinity for a vertical slope whereas the sine approaches unity. The change from tangent to sine reduces the steepness factor S in the USLE from about 19 to 15 for a 50% slope. Insufficient experimental data are available to validate either of these predicted values.

An alternative equation for the slope factor was recommended more recently for USLE application in the Pacific Northwest Wheat and Range Region (McCool et al., 1986):

$$S = (\sin\theta/0.0896)^{0.6} \quad (7)$$

where S is the USLE slope steepness factor. This equation was derived from measured cross sections of rills on slopes ranging from 3 to 53%. Since most of the erosion was caused by surface flow over thawing soils that have a high silt content, little accuracy was assumed lost by omitting estimates of interrill erosion. In an effort to revise the relationship for the slope steepness factor in the USLE, McCool et al. (1987) derived two relationships for mild slopes (with a steepness of less than eight percent) and steeper slopes (equal to or greater than eight percent):

$$S = 10.0\sin\theta + 0.03 \quad \text{for } s < 8\% \quad (8)$$

$$S = 17.2\sin\theta - 0.55 \quad \text{for } s > 8\% \quad (9)$$

McCool's equations provide the basis for revised calculations of topographic parameters in the revised universal soil loss equation (RUSLE, Renard, 1991). One explanation for the distinctions between these two ranges of slope effect is that little or no rill erosion occurs on the gentle slopes, and interrill erosion is not greatly affected by slope (Foster, 1982). When the slope exceeds a critical steepness, rill erosion begins and causes total soil loss to increase rapidly with increasing steepness (Meyer and Harmon, 1985). The idea of rill erosion beginning at a particular (threshold) slope is consistent with theory where the shear power of runoff must exceed a critical shear stress value for the particular soil and surface condition before it begins to detach sediment at defined weakness planes (Meyer et al., 1976; Foster and Lane, 1983). Another factor is that runoff varies more with steepness on mild than on steep slopes. Above eight percent, runoff does not vary significantly with steepness.

Eqs. (8) and (9) apply best to relatively smooth surfaces where tillage is up and down hill, and runoff does not vary with slope for steepness above eight percent. The modifying effect of contour tillage on the soil loss-slope steepness relationship is a management parameter which is incorporated in the USLE supporting practices factor P.

Slope shape and complexity are important modifiers of steepness and length influences on soil erosion. Non-uniformly sloping areas are frequently encountered in the field, on both natural and disturbed areas. Erosion estimates can be erroneous if a uniform slope steepness is assumed on complex slopes; procedures have been developed for improving erosion estimates for such slopes. A description of an empirically-based procedure is given in Agriculture Handbook 537 (Wischmeier and Smith, 1978). It is also important to reconcile the differences between slope length and horizontal length when working with steep slopes. Rainfall energy and intensity data as well as field or watershed areas are normally recorded and calculated on a projected area (horizontal plane) basis. Any field measurements made along the slope should, therefore, be corrected to horizontal length before erosion predictions are made.

Less research has been conducted on the influence of slope length on erosion than on the influence of slope steepness on erosion. Based on available research results, the comparative influences of slope length and steepness on erosion varies greatly. The influence of slope steepness exhibits the wider range in both theory and experimental results. Most slope-length data have been collected on cropland plots or in laboratory flumes of less than 20% slope. Only a handful of researchers have studied length influence on steep slopes such as frequently encountered on tropical upland agroecosystems, temperate rangelands, forest lands, mine spoil areas, and construction sites. Cropland plot studies on slopes of less than 20% indicated a power relationship, as in Eq. (4), with an exponent ranging between 0 and 0.9. An exponent (m) value of 0.5 was suggested by Wischmeier and Smith (1965) for slopes of greater than 5% and is widely used even in the tropics (Hudson, 1971; Roose, 1977; Elwell, 1977).

In the tropics, several authors have confirmed the influence of slope steepness on soil loss (Hudson and Jackson, 1959; Fournier, 1967; Roose, 1975; Lal, 1976). Here also, as expected, soil loss generally increased exponentially with slope steepness. Work on the effects of slope on erosional losses from representative residual and volcanic ash soils in Hawaii under wet antecedent conditions showed that soil erosion in both groups displays a linear dependence on slope steepness (Dangler and El-Swaify, 1976). Insufficient data was collected to allow quantifying slope-length effects. Hudson, 1957, and Dangler and El-Swaify, 1976, concluded that the slope-length exponent may have a different value from that used in temperate zones. Values of m for residual Oahu soils, Hawaii, were 0.67, 0.76, and 1.1 for slopes of 4, 9, and 15%, respectively. These were only preliminary data; however would indicate that slope length (and subsequently the erosivity of overland flow) induces higher erosional losses from the investigated tropical soils than is estimated from the exponents recommended for the U.S. mainland (Wischmeier and Smith, 1978).

McCool et al. (1986) collected the only available field data on the influence of slope length for slopes greater that 20%. Their data from 1973 through 1976 with slopes ranging from 3 to 53%, indicated an exponent value of 0.45. Therefore, based on previous cropland investigations and on McCool et al.'s (1986) cropland investigations, the following Wischmeier–Smith (1978) relationship for slope length is presumed applicable to steep lands:

$$L = (x/22.13)^{m} \tag{10}$$

A comparison of the revised LS factor (RUSLE, Eqs. (8) and (9)) and the original Wischmeier–Smith LS factor (Eq. (6)) shows that LS values for slopes steeper than nine percent are less than those from AH537 (Renard, 1991; Wischmeier and Smith, 1978). For example, at 60% slope, the AH537 LS value is more than twice that of the revised LS value. The reduced LS values for steep slopes are consistent with the general consensus among field users of the USLE that AH537-predicted LS values for steep slopes are too high. For slopes less than nine percent, the revised *LS* values are slightly higher than the AH537 values. It is important to also note that slope factor values from AH537 for slopes less than three percent are questionable because they are an extrapolation of a quadratic equation based on a data set obtained at moderate slopes but which has not been validated at either low or steep slopes.

Similarly, the USLE does not apply to slope lengths shorter than about 4 m (Foster et al., 1981). Little rill erosion occurs on such short lengths and most of the soil loss is by interrill erosion. Instead, Foster (1982) recommends the equation derived from data generated by Lattanzi et al. (1974) for estimating interrill erosion:

$$S = 3.0(\sin\theta)^{0.8} + 0.56 \tag{11}$$

Lattanzi et al. (1974) used 0.61 m long slopes under simulated rainfall. Eq. (11) is further confirmed by studies of Singer and Blackard (1982), Evett and Dutt (1985), and Rubio-Montoya and Brown (1984).

Unfortunately, quantitative data are unavailable on the extent to which *LS* predictions can be generalized among soils with different surface properties, including erodibility. Evidence abounds that the relationship between soil loss and slope characteristics varies greatly with soil, tillage, cover, runoff initiation time and magnitude, and other factors. Discontinuities exist between the slope effect equation for short slopes and that for long slopes. Both the USLE (Wischmeier and Smith, 1978) and RUSLE (Renard, 1991) lump rill and interrill erosion components and assume no interdependence among individual predictive factors. The latter, however, now includes refinements in quantifying topographic influence which allow distinguishing between land surfaces based on the likely (slight, moderate, or high) degree of rilling. It also has provisions for calculating *LS* factors for complex slopes without having to assume slope uniformity. Fundamentally-based process-models would allow the separation of component effects for rainfall and runoff, distinction of detachment from interrill and rill areas, as well as transport and deposition of sediment by overland flow. This would also greatly facilitate consideration of other factors influencing erosion in providing realistic quantitative predictions of topographic effects.

4. Influence of other site characteristics on erosion

Most of the information available for quantifying the influence of site parameters on erosion are site-specific. Similarly, the available models recommended for their application are empirically derived and designed for temperate, 'conventional' crop lands. The interactions among a site's climate, soil and topography are not universally uniform. Unfortunately, the data-bases for rainfall and runoff erosivity, and for soil erodibility (detachability, transportability, entrainability, rillability, gullying or mass-wasting potential, and depositional potential) are scarce, at best, for hilly areas in general and those in the tropics and subtropics in particular. Few validations have been made of available predictive empirical or process models in such areas.

Deficiencies in the technical information base have also perpetuated the excessive dependence on what seem to be universal but actually are site-specific and arbitrarily prescribed engineering practices for erosion control, including specifications for terracing and drainage provisions (El-Swaify et al., 1982). Recent trends in the refinement of empirical models and formulation of process-based erosion models promise to rectify some of the deficiencies in technology transfer (Laflen and Onstad, 1994). Ideally, a compromise is needed to reconcile the two approaches and assure that existing information is effectively used in new initiatives.

Land use systems and employed management practices depend on the site's potential for supporting agricultural development and on the socioeconomic environment. Implemented land use systems, in turn, determine whether the vast erosion potential in these vulnerable regions (often exceeding tens or hundreds of tons of soil loss per hectare per year) will be effectively controlled or proceed unabated. Judicious selection and design of cropping systems, land management systems, and water management systems are necessary to attain effective runoff and erosion control. With the emergence of the 'land husbandry' focus, it is now also increasingly recognized that the role of productivity-enhancing crop and soil management practices may be more important than structural erosion control measures in imparting long-term sustainability and assuring farmer acceptance and cooperation. The 'uniqueness' of tropical steeplands extends to their complex and highly diverse land uses, very few of which have been studied from the erosion vulnerability perspective. A brief discussion of these aspects is presented below.

4.1. Cropping systems

Vegetation and cultural attributes which determine vulnerability to (or protectiveness against) erosion are the size (extent and height), shape, structure, architecture, and growth characteristics of individual plant canopies within the community; the shear total quantity of live above ground biomass; residue cover and its decomposition dynamics; soil surface roughness, and the sequence and timing of various human-applied actions. Systems which need evaluation for suitability of use on steep hillslopes include conventional food crops (grown as sole crops, mixed crops, relay crops, ratoons, sequentially, in rotation, or as intercrops), agroforestry systems (including alley-cropping or other perennial hedge-row systems), pasture-animal grazing systems, and combinations of these. Selection and design of a land use system is probably the most critical step which must match the inherent attributes of the site to allow optimal productivity to meet the food, feed, fiber, fuel, and cash needs of the community, and also be compatible with the conservation needs of the natural resource base. Once the optimal land use is implemented, high productivity can be sustained by adopting wise agronomic practices (crop and soil husbandry); and this in turn assures efficient use of applied inputs and effective soil and water conservation (El-Swaify, 1994).

Including perennial vegetation in cropping cycles is necessary, particularly in unirrigated marginal rainfall regions, to assure year-around protection by continuous cover and to provide degradation-preventing year-around biological activity within the soil. Other known benefits of such vegetation result from specialized use as living sediment traps or barriers in hedge rows, as sources of organic residue amendments, and (with trees) improved soil anchoring and stabilization against mass movement by deep root penetration (El-Swaify, 1994). Rapidly growing cover crops, preferably legumes, can be strategically used to provide direct soil protection either by intercropping or precropping. Such strategy also results in soil nitrogen enrichment when legumes are used in combination with the annual crops. Strategies for use of crop residues should include optimal return of residues to the soil for direct protection against erosional losses, reduced loss and improved storage of soil-water, maintenance of adequate soil organic matter levels and fertility, and long-term buildup of soil structure. It is clearly recognized that residue is subject to many competitive uses in many developing countries, primarily for fodder and fuel. Nevertheless, conservationists should be provided the opportunity to demonstrate the benefits of residue cycling, recognizing the fact that even partial surface cover can provide effective protection against erosion (Fahrney et al., 1987).

Tree plantings, as afforestation areas or commercial orchards, are often advocated as protective land use systems on steep lands. Some successful examples can be seen involving intensive horticultural use of such lands, but with high capital inputs (e.g. Koh et al., 1991). However, it has been repeatedly demonstrated that tree cultures in the absence of surface cover can be subject to higher erosion rates than conventional crops, and sometimes, bare soils (El-Swaify, 1992). Where ground cover or low storey vegetation cannot thrive due to excessive shading, a deliberate strategy of ground cover and or organic residue or litter management must be used.

Although this discussion emphasized vegetation role, it is important to recognize the role of animals in tropical hill lands as well. Domesticated animals can play both a destructive and constructive role in agroecosystems, depending on their population, available resources for meeting their grazing needs, and how they are managed. Recycling of animal waste, where available, can achieve substantial benefits to agroecosystem productivity.

4.2. Land and soil management

Practices which require evaluation from the perspective of conservation-effectiveness, aside from overcoming chemical and infertility constraints, include the manipulation of soil surface roughness and configurations, selection of appropriate tillage systems, and modification of soil structure. As with cropping systems, selection and design of such practices must be compatible with climatic and soil characteristics, and be based on both productivity benefits and runoff-erosion control considerations (Koh et al., 1991). Special care must be exercised to avoid failures arising from extreme slope gradients or unstable geologic strata. For instance, land surface configurations intended to maximize water infiltration (e.g. contour bunds or terraces) may pause serious erosion danger due to breaching in structurally non-stable soils. Ponding of terraces for paddy culture atop poorly drained or impermeable strata may also lead to mass movement and landslides (Soleh Sukmana, personal communication, Center for Soil and Agroclimatic Research, Bogor). Ridge-furrow or terrace configurations intended for controlling runoff may expose low-fertility or impermeable layers of certain soils and, so, decrease overall productivity and ultimately increase runoff and erosion as compared with flat cultures. Similarly, intensive inversion-type primary tillage intended for improving crop root environment may increase the silt content of surface layers and exacerbate surface sealing, crusting, and runoff generation potential of soils with a coarse-textured surface and an argillic lower horizon (e.g. Alfisols and Ultisols). Where soils have not degraded structurally so as to inhibit effective seed germination and crop establishment, the adoption of 'reduced tillage' systems may be encouraged (Lal, 1976), particularly where crop residue is abundant and available for recycling.

4.3. Water management

On all rainfed lands, particularly steeplands, a high priority should placed on managing excess runoff water safely and productively. Overall field design and applied tillage and land surface shaping operations must be conducted in the context of 'watershed-ecosystems' so as to provide for the effective intake of rainfall and efficient management of runoff (e.g. El-Swaify et al., 1985). Continuing cognizance of all components of the water balance is particularly critical in rainfed regions, and more so in marginal rainfall areas such as semi-arid, sub-humid, or other regions with strictly seasonal rainfall. Minimum waste and efficient use of water by the crop is an important component of strategies aimed at sustained productivity. The safe disposal of excess runoff through stable intra-catchment (inter-terrace) waterways is critical for overall stability. Waterways and drainage ways should possess the capacity, slope gradient, and length that are adequately designed to cope with the prevailing rainfall regime and generated runoff. In marginal rainfall areas, the harnessing of excess runoff and/or development of other water sources may be necessary for life-saving supplemental irrigation. Water storage structures (tanks, reservoirs), must be properly sealed and means of recycling and optimally using stored water for irrigation devised. The likelihood of successfully harvesting water in this manner or from 'dedicated' areas within the catchment must be assessed using long term probability analysis of rainfall patterns and runoff models (El-Swaify et al., 1985). It is critical to remember that the likelihood of harvesting runoff for use during dry spells diminishes with the increasing frequency of such spells. The 'total catchment' concept applies to ground water replenishment and mining as well. This source of water is more likely to provide evenly distributed amounts of water (less seasonal fluctuations) for use in periods when stores of surface runoff are diminished. A major feature of water harvesting and ponding in small reservoirs is the potential utility for aquaculture applications.

5. Socio-economic and policy factors

Increasing concern with erosion problems, global recognition that natural resource degradation in many countries is nearing the point of no return, and the urgent need to sensitize and secure commitments from members of the International community, have led to the adoption, in 1982, of a World Soils Charter by the Food and Agriculture Organization of the United Nations. The Charter sets forth principles for wise, productive, and protective land use to assure the welfare of future generations. This and subsequent important and necessary declarations, such as Agenda 21 arising from the Rio June 1991 Earth Summit, will be of limited value if individual countries, relevant institutions within them, and the land users themselves are not supportive or committed to carrying out needed changes in land use or the enactment of protective national and regional laws and strategies. Very often, the first and most important step in securing such support and commitment is to convey to land users and policy makers a clear understanding of the causes, extent, and impacts of erosion. Such sensitization and increased awareness can now be amply supported by evidence, quantitative data, and valid models that are available for addressing concerns based on all three aspects.

In addition to educational, informational, and awareness issues, several other socioeconomic elements are needed to assure conservation-effective land use (Napier et al., 1994). These include the availability of a thorough land resource inventory and a clear national policy on land use priorities, adequate land tenure systems, reduced fragmentation or appropriate allocation of land parcels due to inheritance or other ownership transactions, reduced cost and risk of adopting improved technology, availability of effective extension services for guiding designs for protective land use, efficient enforcement of land-use policies, sufficient incentive for sustained adoption of erosion-preventing practices, meaningful involvement of all levels, particularly grass-root levels of the farming community (e.g. farmers) in developing conservation technology, and a strong commitment to the regular monitoring of erosion and its indicators to assure the continued stability of the natural resource base.

6. Designing conservation-effective agroecosystems for steeplands

Selecting appropriate land uses for steep slopes is the best and most 'protective' approach for avoiding accelerated water erosion. The multitude of agronomic and engineering options available for controlling erosion is impressive. Steeply sloping lands are often subjected to labor intensive and expensive structural engineering and land shaping measures (e.g. terracing) as part of any agricultural development. As detailed in the previous section, the physical basis for establishing the need for and then designing such measures anywhere, let alone on steeplands, is presently deficient. Much of what is prescribed involves arbitrary judgement, emphasis on 'visibility' to impress development donors, and little effort to match the design (and possibly reduce its cost) with soil and climatic characteristics. In addition, frequently to the detriment of these expensive investments, agronomic measures and wise land husbandry in common property or inter-terrace areas (between individual farm holdings) are often neglected.

It is quite probable that simple, well-designed agronomic practices can, by themselves, provide sufficient alleviation of runoff and erosion to minimize the need for engineering measures. Unfortunately, no quantitative data have been developed or applied to determine the upper slope limits beyond which such agronomic practices may be ineffective and mechanical measures become necessary for runoff and erosion control.

7. Conclusions

Despite indications by some experts to the contrary (Foster et al., 1980), certain important gaps still exist in the knowledge currently available for quantitatively predicting and controlling erosion from steep slopes. Also deficient are the experimental data bases at the scale necessary for estimating field and catchment-based runoff, soil losses and sedimentation; for quantifying the effects of soil taxa on the design criteria for erosion control; and for quantifying the benefits of improved soil and crop management practices to resource conservation on these harsh landscapes (El-Swaify, 1994).

Another important consideration is that soil losses by gullying and mass-wasting mechanisms (e.g. landslides) remain far from being quantitatively predictable. Often, these forms of erosion are more important than surface erosion phenomena in uplands and highlands, even without human influences. Tree-based systems, preferably natural forests, are likely to be more beneficial in these settings than even the most carefully tailored agronomic and structural measures of soil conservation.

Socio-economic-cultural elements which characterize land users in upland and highland regions are often different from those of lowland inhabitants. These must also be understood and taken into account if improved conservation technologies are to be adopted by them at the scale which is necessary to ensure overall stability in the cultivated steeplands of the humid tropics. Participatory research and planning approaches are critical for this purpose.

The benefits of effective conservation to the stability, productivity, and sustainability of the resource base and to the quality of downstream environments are convincing. Policy makers should provide aggressive leadership to land use planners and other public agents to encourage incorporating available conservation knowledge into land use and management for hillslope regions. In addition, research targeted for filling information gaps deserves solid support to achieve improved erosion predictions and rational conservation plans for the natural resources of these regions.

References

Dangler, E.W. and El-Swaify S.A., 1976. Erosion of selected Hawaii soils by simulated rainfall. Soil Sci. Soc. Am. J. 40(5): 769–773.

El-Swaify, S.A., 1992. Soil conservation research in Hawaii – A case study for the tropics. Aust. J. Soil Water Conserv. Special International Issue 5(3): 9–13.

El-Swaify, S.A., 1994. State-of-the-art for assessing soil and water conservation needs and technologies. In: Adopting Conservation on the Farm: An International Perspective of the Socioeconomics of Soil and Water Conservation. Soil and Water Conservation Society, Ankeny, pp. 13–27.

El-Swaify, S.A., E.W. Dangler and Armstrong C.L., 1982. Soil Erosion By Water in the Tropics. Research and Extension Series 024. Hawaii Institute of Tropical Agriculture. University of Hawaii Press, Honolulu.

El-Swaify, S.A., Garnier, C.L. and Lo A., 1987. Recent advances in soil and water conservation on steep lands. In: Steepland Agriculture in the Humid tropics. Tay, Mukhtarrudin, and Zahari (Editors). Proc. International Conf.on Steepland Agriculture, MARDI/MSSS, Serdang, Selangor, Malaysia, pp. 265–308.

El-Swaify, S.A., Pathak, P., Rego, T.J. and Singh, S., 1985. Soil management for optimized productivity under rainfall conditions in the semi-arid tropics. Advances in Soil Science, Vol. 1, Springer Verlag, New York, pp. 1–64.

Elwell, H.A., 1977. A soil loss estimation for southern Africa. Res. Bull No. 22, Causeway, Rhodesia (Zimbabwe), Dept. of Conservation and Extension.

Evett, S.R. and Dutt, G.R., 1985. Effect of slope and rainfall intensity on erosion from sodium dispersed, compacted earth microcatchments. Soil Sci. Soc. Am. J. 49(1): 202–206.

Fahrney, K.S, El-Swaify, S.A., Lo, A.K.F. and Joy, R., 1987. Maize yields and soil loss with conservation and conventional tillage practices on a tropical Aridisol. In: Role of Legumes in Conservation Tillage Systems. Soil and Water Conservation Society, Ankeny, pp. 138–140.

Foster, G.R., 1982. Modeling the erosion process. In: Hydrologic Modeling of Small Watersheds, C.T. Haan (Editor), ASAE Monograph No. 5, St. Joseph, MI, pp. 297–380.

Foster, G.R. and Lane, L.J., 1983. Erosion by concentrated flow in farm fields. In: Proc. of the D.B. Simons Symp. on Erosion and Sedimentation, Colorado State University, Ft. Collins, CO, pp. 9.52–9.82.

Foster, G.R., Lane, L.J., Nowlin, J.D., Laflen, J.M. and Young, R.A., 1980. A model to estimate sediment yield on field-sized areas: Development of method. In: CREAMS: a field scale model for Chemicals, Runoff, and Erosion from Agricultural Management Systems. USDA-SEA. Conserv. Res. Rep. No. 26, pp. 36–64.

Foster, G.R., Simanton, J.R., Renard, K.G., Lane, L.J. and Osborn, H.B., 1981. Discussion of Application of the Universal Soil Loss Equation to rangeland on a per-storm basis. J. Range Manage. 34(2): 161–165.

Fournier, F., 1967. Research on soil erosion and soil conservation in Africa. Sols Afr. 12: 53–96.

Horton, R.E., 1945. Erosional development of streams and their drainage basins: Hydrophysical approach to quantitative morphology. Bull. Geol. Soc. Am. 56: 275–370.

Hudson, N.W., 1957. Erosion control research. Progress Report on experiments at Henderson Research Station, 1953–1956. Rhod. Agric. J. 54(4): 297–323.

Hudson, N.W., 1971. Soil Conservation. Cornell University Press, Ithaca, NY.

Hudson, N.W. and Jackson, D.C., 1959. Results achieved in the measurement of erosion and runoff in southern Rhodesia. Proc. Inter-African Soils Conf. Compte Rendus 3: 575–583.

Koh, C.C., Liao, M.C., Lee, S.W. and Cheng, J.D., 1991. The evolution of conservation farming in Taiwan. In Development of Conservation Farming on Hillslopes. Soil and Water Conservation Society, Ankeny, pp. 3–11.

Laflen, J.M. and Onstad, C.A., 1994. State-of-the-art in technology development for soil conservation and water quality. In: Adopting Conservation on the Farm: An International Perspective of the Socioeconomics of Soil and Water Conservation. Soil and Water Conservation Society, Ankeny, pp. 29–35.

Lal, R., 1976. Soil erosion problems on an Alfisol in western Nigeria, and their control. Monograph No. 1. IITA, Ibadan, Nigeria.

Lattanzi, A.R., Meyer, L.D. and Baumgardner, M.F., 1974. Influence of mulch rate and slope steepness on interrill erosion. Soil Sci. Soc. Am. Proc. 38(6): 946–950.

McCool, D.K., Zuzel, J.F., Istok, J.D., Formanek, G.E., Molnal M. and Saxton, K.E., 1986. Erosion processes and prediction for the Pacific Northwest. Proc. of the 1986 National Steep Symp. Spokane, WA, May 20–21, in press.

McCool, D.K., Brown, L.C., Foster, G.R., Mutchler, C.K. and Meyer, L.D., 1987. Revised slope steepness factor for the Universal Soil Loss Equation, in press.

Meyer, L.D. and Harmon, W.C., 1985. Sediment losses from cropland furrows of different gradients. Trans. ASAE 28(2): 448–453, 461.

Meyer, L.D., DeCoursey, D.G. and Romkens, M.J.M., 1976. Soil erosion concepts and misconceptions. Proc. of the Third Federal Interagency Sedimentation Conf. 2.1–2.12, Sedimentation committee of the Water Resources Council. PB-245 100, Denver, CO.

Musgrave, G.W., 1947. The quantitative evaluation of factors in water erosion – A first approximation. J. Soil Water Conserv. 2: 133–138, 170.

Napier, T.L., Camboni, S.M. and El-Swaify, S.A., 1994. Adopting Conservation on the Farm: An International Perspective of the Socioeconomics of Soil and Water Conservation. Soil and Water Conservation Society, Ankeny.

Packer, P.E., 1951. An approach to watershed protection criteria. J. Forest. 49: 639–644.

Renard, K. (Editor), 1991. Predicting Soil Erosion by Water – Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE). ARS, USDA, TUCSON.

Renner, F.G., 1936. Conditions influencing erosion on the Boise River watershed. USDA Tech. Bull. 528, pp. 32.

Roose, E.J., 1975. Erosion et ruissellement en Afrique de l'ouest. Vingt annees de mesures en petites parcelles experimentales. Abidjan: ORSTOM.

Roose, E.J., 1977. Use of the universal soil loss equation to predict erosion in west Africa. In: G.R. Foster

(Editor), Soil Erosion: Prediction and Control. Spec. Publ. No. 21, Soil Conserv. Soc. Am., Ankeny, IA, pp. 60–74.

Rubio-Montoya, D. and Brown, K.W., 1984. Erodibility of strip-mine spoils. Soil Sci. 138(5): 365–373.

Singer, M.J. and Blackard, J., 1982. Slope angle-interrill soil loss relationships for slopes up to 50%. Soil Sci. Soc. Am. J. 46(6): 1270–1273.

Smith, D.D. and Wischmeier, W.H., 1957. Factors affecting sheet and rill erosion. Trans. Am. Geophys. Union 38(6): 889–896.

Wischmeier, W.H. and Smith, D.D., 1965. Predicting rainfall-erosion losses from cropland east of the Rocky Mountains. Agric. Handbook 282, USDA, Agric. Res. Serv., pp. 47.

Wischmeier, W.H. and Smith, D.D., 1978. Predicting rainfall erosion losses. Agric. Handbook 537, USDA, SEA, Agric. Res., pp. 58.

Zingg, A.W., 1940. Degree and length of land slope as it affects soil loss in runoff. Agric. Eng. 21(2): 59–64.