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Land Erodibility Assessment Methodology

LEAM, Using Soil Survey Data Based On *Soil Taxonomy*

LUIS A. MANRIQUE

University of Hawaii

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Foreword

Because of the key role that soil and water management play in improving productivity in semi-arid regions, an agreement was developed between the Agricultural Research Service (ARS) of the U.S. Department of Agriculture (USDA) and the Bureau for Science and Technology of the U.S. Agency for International Development (AID) to provide technical expertise for improving management of soil and water resources in the developing world. This agreement resulted in the current project Technology for Soil Moisture Management (TSMM).

To develop more sustainable agricultural systems in the developing world, resource management must address the problem of soil erosion and water runoff. TSMM is addressing the problem of low productivity in many soils which is the result of improper soil management practices also resulting in erosion and environmental degradation, both on- and off-site. The integrity and stability of the environment is increasingly recognized as a major focus of international development. What is not as well recognized is the extreme scarcity of reliable quantitative data on erosion and runoff which constrains our ability to develop and implement effective strategies.

The urgent need for increased public awareness and planning to reduce soil erosion requires maximum use of whatever qualitative or empirical information is available in the absence of quantitative information. Dr. Manrique's previous experience with the International Potato Center in Peru, and more recently with the International Benchmark Sites Network for Agrotechnology Transfer Project has provided him with a broad-based experience in climatic and soil data analyses and interpretation. His innovative ability to relate his experience and technical abilities to practical and realistic ends is evident in this publication.

Soil survey information is frequently available in various formats but is rarely used to the extent desirable. Survey information based on *Soil Taxonomy* contains a wealth of information for various uses that can be extracted by technically trained and qualified individuals. This publication is a result of an attempt to make maximum use of soil survey information. It provides one more approach to use in planning for improving the appropriate placement of investments in those agricultural areas of greatest needs and returns for improved productivity and environmental quality. TSMM is pleased to assist in this effort.

Raymond E. Meyer

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The author is solely responsible for all ideas contained in this book.

Preface

Land erodibility assessment in developing countries is often constrained by the lack of a methodology capable of assessing, from limited and often incomplete soils and climatic data, the potential erosion risk of agricultural lands. This book describes the **Land Erodibility Assessment Methodology (LEAM)** designed primarily for use in developing countries. LEAM assesses the potential erosion risk of lands in quantitative and operational terms by using information contained in soil surveys based on *Soil Taxonomy*. Assessment of potential erosion risk is based on three land characteristics: *(1)* slope hazard, *(2)* rainfall erosivity risk, and *(3)* intrinsic soil erodibility. Each land characteristic is subsequently defined by other land characteristics such as slope steepness and length, soil moisture regime, and particle-size class and mineralogy class. The LEAM rating framework provides basic information as to whether a given land has a certain potential risk, and describes the agricultural limitations associated with that risk.

Luis A. Manrique

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Part One

INTRODUCTION

The constraining factor of land erodibility assessment in developing countries is often the lack of a methodology capable of assessing potential erosion risk of agricultural lands from limited and often incomplete soils and climatic data. Soil surveys compile large quantities of data, however, only a small fraction can be used for erosion assessment. Inefficient use of soil survey data arises because the information is rarely presented in ways that can benefit people who have a limited background in soil erosion and soil conservation. The Land Erodibility Assessment Methodology (LEAM) is designed primarily for use in developing countries, using a systematic procedure which extracts information from soil surveys based on *Soil Taxonomy* (Soil Survey Staff, 1975); that information is then used to define and categorize potential erosion risk in quantitative and operational terms.

RATIONALE

Land erodibility results from the interaction of land characteristics such as slope steepness, slope length, soil permeability, soil texture and structure, crop cover, rainfall duration and intensity, among many others. A practical way to assess land erodibility is to predict soil losses from a particular land under a set of environmental conditions and crop management practices. Wischmeier and Smith (1965) developed a parametric model known as the Universal Soil Loss Equation (USLE) which is expressed in the equation,

$$A = R \times K \times L \times S \times C \times P \qquad [1]$$

where, A is soil loss, R is rainfall erosivity, K is soil erodibility, L is slope length, S is slope steepness, C is crop management, and P is conservation practice. Equation [1] relates the expected soil loss, A, to land erodibility as expressed by land characteristics R, K, L, and S; and to the current type of land use as expressed by C and P. In spite of numerous soil loss studies conducted to test the usefulness of the USLE, some parameters of Equation [1], particularly those necessary to assess land erodibility, are still not readily available (Armstrong *et al.*, 1980). This has precluded more extensive use of the USLE. The rainfall erosivity (R), for example, is probably one of the most difficult parameters to obtain, especially in areas with insufficient weather records (Lal *et al.*, 1980).

METHODOLOGY

Land erodibility is defined in this study by three major land characteristics: *(i)* slope hazard, *(ii)* rainfall erosivity risk, and *(iii)* soil erodibility K. Each major land characteristic is subsequently defined by other land characteristics known as diagnostic criteria (Table 1). In the absence of main diagnostic criteria, alternative diagnostic criteria are provided for each land characteristic.

Table 1. Diagnostic criteria used to define land characteristics associated with land erodibility.

Land Characteristic	Main Diagnostic Criteria	Alternative Diagnostic Criteria
Slope Hazard (S)	Slope Factor (LS)	Slope Steepness
Rainfall Erosivity Risk (RR)	Modified Fournier's Index (RI)	Moisture Availability Index (MAI), Soil Moisture Regime
Soil Erodibility (K)	Soil Erodibility K	Particle-size Class and Mineralogy Class, and Mineralogy Group

Assessing Slope Hazard

Slope steepness (S) and slope length (L) determine the topographic input in the USLE. Of the two land characteristics, slope steepness is generally available in most soil surveys. In areas with no previous history of soil survey studies, the use of aerial photographs and photointerpretation techniques can be of great value in separating and ranking the slope steepness of physiographic units. On the other hand, slope length is difficult to assess from soil survey data unless large topographic maps are available. The slope factor (LS), as defined in the USLE, is the diagnostic criterion used in LEAM to assess slope hazard (Table 2), and is calculated by the following equation (Mitchell and Bubenzer, 1980):

$$LS = (X/22.13)^m \times (0.065 + 0.045 \times S + 0.0065 \times S^2) \qquad [2]$$

where, X is slope length in meters, m is a constant factor depending upon slope steepness, and S is percent slope steepness. The following algorithms apply for m (Wischmeier and Smith, 1978).

If $S < 1$ then $m = 0.2$
If $1 \leq S \leq 3$ then $m = 0.3$
If $5 < S > 3$ then $m = 0.4$
If $S \geq 5$ then $m = 0.5$

If slope length is unavailable, then the slope hazard is assessed solely from slope steepness (Table 2). The assumption is that with increasing slope steepness, slope length declines and so its effect on erosion (Lal, 1976).

Defining Rainfall Erosivity Risk

Modified Fournier's Index. The main diagnostic criterion proposed for rainfall erosivity risk in the LEAM is the modified Fournier's Index (R_I) which is defined as follows (Arnoldus, 1980):

$$RI = \sum_{1}^{12} (MR)^2 / AR \qquad [3]$$

where, MR and AR are monthly and annual millimeters of rainfall, respectively. A close relation-

Table 2. Main and alternative diagnostic criteria used to develop slope hazard classes.

Slope Hazard Class		Slope Factor (LS)	Slope Steepness (%)
S1	Low	0-2	0-10
S2	Moderate	2-4	10-20
S3	High	4-6	20-30
S4	Very High	> 6	> 30

ship (r^2 = 0.83 and 0.72, respectively) was found between RI and the R factor of USLE when tested in West Africa (n = 177 stations) and the United States (n = 244 stations) (Arnoldus, 1980).

To study changes in RI with changes in soil moisture regimes, RI values were calculated from rainfall data for soils where selected meteorological stations were located (Appendix 1). Soil names were obtained by identifying the soil series of the selected meteorological stations using large-scale soil survey maps. The taxonomic name at the family category (Soil Survey Staff, 1975) was obtained from the soil series name (SCS, 1978). The RI values for these selected soils increased as the soil moisture regimes became wetter (Table 3). Extreme soil moisture regimes, that is, the perudic and aridic, had distinctive RI values; whereas, some overlapping in RI values was noted among intermediate soil moisture regimes.

Moisture Availability Index. Another alternative diagnostic criterion proposed for rainfall erosivity risk is the moisture availability index (MAI) which is defined as the following (Hargreaves, 1977):

$$MAI = PD / ETP \qquad [4]$$

where, PD is dependable rainfall determined by the 75% probability of rainfall occurrence, and ETP is potential evapotranspiration. Although MAI was designed to indicate moisture adequacy for plant growth, it can be used to predict drainage needs (Hargreaves, 1977). In environments having 1 or 2 months with values of MAI > 1.3, for example, surface drainage was generally found to produce large benefits on slopes up to 2%, and on irregular slopes up to 3%.

The rationale of using MAI as a diagnostic criterion for rainfall erosivity risk is based on two factors. First, MAI is computed from 75% probability of rainfall occurrence rather than from actual rainfall occurrence, thus minimizing the risk of an inaccurate assessment of rainfall erosivity risk in areas with large rainfall variability. Second, MAI directly expresses the potential crop yield relationship to water availability; and indirectly expresses water availability relationship to erosion risk.

Table 3. Modified Fournier's Index (RI) values for soils with different soil moisture regimes.

Soil	RI value
Perudic Moisture Regime	
Hilo	302.79
Alto Tapajos	303.53
Coari	229.28
Ponape	420.65
Mean	*314.96 (79.13)*[*]
Udic Moisture Regime	
Curitiba	126.73
Olinda	225.93
Charleston	122.23
Olympia	157.53
Mean	*158.11 (47.86)*
Ustic Moisture Regime	
Aracaju	150.03
Rio de Janeiro	106.93
Brownsville	70.82
Lihue	104.71
San Antonio	64.50
Mean	*99.40 (34.22)*
Xeric Moisture Regime	
Bechar	10.06
La Rioja	45.80
Mean	*27.93 (25.27)*
Aridic Moisture Regime	
El Paso	21.51
Honolulu	64.13
Luanda	78.36
Mean	*54.67 (29.58)*

[*] Numbers in parentheses are standard deviation values.

Consequently, the likelihood of greater yields, as water availability increases, is also matched by greater erosion risk.

Table 4. Proposed criteria used to rate rainfall erosivity risk classes of the LEAM based on RI and MAI values, and soil moisture regimes.

Rainfall Erosivity Class	Erosivity Risk	Diagnostic Criteria	
		Main	Alternative
RR1	Very Low	RI < 50	All 12 months with MAI ≤ 0.5 and 10 months or more with MAI < 0.25, or an **aridic moisture regime**.
RR2	Low	RI 50-100	All 12 months with MAI ≥ 0.25 and 5 months or more with MAI ≤ 0.5; or all 12 months with MAI ≤ 0.5 and 9 months or less with MAI < 0.25, or a **xeric moisture regime**.
RR3	Moderate	RI 100-200	All 12 months with MAI > 0.5 and 4 months or less with MAI ≥ 1.0; or all 12 months with MAI ≥ 0.25 and 4 months or less with MAI ≤ 0.5, or an **ustic moisture regime**.
RR4	High	RI 200-300	All 12 months with MAI > 0.5 and 4 to 8 months with MAI ≥ 1.0 or an **udic moisture regime**.
RR5	Very High	RI >300	All 12 months with MAI > 0.5 and 9 months or more with MAI ≥ 1.0, or a **perudic moisture regime**.

Soil Moisture Regime. The soil moisture regimes described in *Soil Taxonomy* (Soil Survey Staff, 1975) are also used as alternative diagnostic criteria for rainfall erosivity risk, and are expressed in terms of MAI (Table 4). The criteria for characterizing soil moisture regimes in terms of MAI was developed by Manrique (1982) who analyzed soil water balances of the soil profiles included in *Soil Taxonomy's Appendix 4*. The logic of that criteria was tested by comparing MAI values of soil moisture regimes for soils where selected meteorological stations were located (Appendices 1 and 2). Perudic, xeric, and aridic moisture regimes had MAI values (Table 5) that agreed quite well with the criteria proposed for such moisture regimes (Table 4). Some udic moisture regimes had at least three months with values of MAI < 0.25, and this differed significantly from the proposed criteria that udic moisture regimes should have values of MAI > 0.5. These udic regimes apparently had dry periods that were long enough to make them transitional to ustic moisture regimes. Similarly, two ustic regimes had 9 to 10 months with values of MAI < 0.25; these soils seem to have a moisture regime drier than ustic. More MAI data from different soil moisture regimes are needed to refine the criteria established in Table 4. Meanwhile, from a practical standpoint, the proposed criteria is comprehensive enough for MAI values to reflect differences in soil moisture regimes.

Determining Soil Erodibility

The soil erodibility factor can be determined from soil characteristics (Wischmeier and Mannering, 1969; Wischmeier *et al.*, 1971). The soil erodibility nomograph developed by Wischmeier *et al.* (1971) was used in this study to calculate K of the surface layer of 74 United States soils included in *Soil Taxonomy's Appendix 4*, and 12 Panamanian soils (Jaramillo *et al.*, 1985). The K values for all soils are shown in Appendix 3.

Soil permeability values needed to compute K were obtained by relating soil texture to a specific permeability class (Table 6). The K values for 86 soils, grouped according to particle-size and mineralogy classes, and mineralogy groups are presented in Table 7. To look at mixed mineralogies in more detail with regard to their intrinsic soil erodibility, soils having similar particle-size class and belonging to the same mineralogy class were grouped according to their dominant clay mineral content based on approximate weight fractions (X-ray). Subsequent partitioning of mixed mineralogy classes into different mineralogy groups allows adjustments to be made on K for the dominance of a given clay mineral.

Very low and low K values (< 0.20) were found in sandy particle-size classes with mixed or siliceous mineralogies, and in clayey particle-size classes with oxidic or kaolinitic mineralogies (Table 7). Coarse-loamy and clayey soils also had low K values (< 0.20) when their mixed mineralogy was dominantly kaolinitic, halloysitic, or vermiculitic. Thixotropic soils had high K values compared to the low values reported for volcanic ash soils from Hawaii (Dangler *et al.*, 1976). This may be due to the low soil permeability values used in estimating K. Under field conditions, however, volcanic ash soils have high soil permeability comparable to sandy or highly aggregated soils. Soils with fine-loamy, fine-silty, or fine particle-size classes, and mixed mineralogy but dominantly montmorillonitic; and soils with clayey particle-size class and montmorillonitic mineralogy had values of K > 0.30. Within these particle-size classes, soils with mixed mineralogy but dominantly kaolinitic or halloysitic had values of K < 0.30. The data in Table 7 indicate a close relationship between K values and particle-size and mineralogy classes and mineralogy groups. This close relationship was used as rationale to select particle-size class, mineralogy class, and mineralogy group as alternative criteria to estimate K.

Table 5. Number of months within MAI range for soils with different soil moisture regimes.

Soil	MAI Range			
	>1.0	1.0-0.5	0.5-0.25	< 0.25
Perudic				
Hilo	11	1	0	0
Alto Tapajos	7	2	1	2
Coari	7	2	3	0
Ponape	12	0	0	0
Mean	*9.3*	*1.3*	*1.0*	*0.4*
Udic				
Curitiba	1	9	2	0
Olinda	3	2	1	6
Charleston	0	5	6	1
Olympia	6	0	2	4
Mean	*2.5*	*4.0*	*2.8*	*2.8*
Ustic				
Aracaju	2	3	1	6
Rio de Janeiro	0	2	7	3
Brownsville	0	0	2	10
Lihue	0	4	3	5
San Antonio	0	0	3	9
Mean	*0.4*	*1.8*	*3.2*	*6.6*
Xeric				
Bechar	0	0	0	12
La Rioja	0	0	0	12
Mean	*0*	*0*	*0*	*12.0*
Aridic				
El Paso	0	0	0	12
Honolulu	0	0	0	12
Luanda	0	0	1	11
Mean	*0*	*0*	*0.3*	*11.7*

Source: Manrique, 1982.

Table 6. General relationship between soil textural classes, particle-size distribution, mean diameter, and soil permeability (SP).

Textural Class	Sand (%)	Silt (%)	Clay (%)	Mean Diameter (mm)	SP (cm/h)	Permeability Class (SCS, 1951)
Coarse sand	--	--	--	--	492.0	Rapid
Sand	95	3	2	0.29	49.3	Rapid
Fine sand	--	--	--	--	19.8	Rapid
Very fine sand	--	--	--	--	9.8	Rapid
Loamy sand	83	10	7	0.25	5.0	Moderately Rapid
Sandy loam	55	25	20	0.17	1.0	Moderate
Very fine sandy loam	--	--	--	--	0.5	Moderately Slow
Loam	40	40	20	0.12	0.2	Slow
Silt loam	22	65	13	0.07	0.1	Slow
Silty clay loam	10	55	35	0.04	0.05	Very Slow
Silty clay	6	47	47	0.02	0.01	Very Slow
Clay	40	10	50	0.12	0.005	Very Slow

Source: Horn, 1971.

Table 7. Soil erodibility (K) values grouped according to particle-size class, mineralogy class, and mineralogy groups.

Particle-size Class	Mineralogy Class	Mineralogy Group*	No. Soils	K
Loamy-skeletal	Mixed	All soils	3	0.41 *(0.11)***
Clayey-skeletal	Montmorillonitic, kaolinitic	All soils	2	0.24 *(0.12)*
Sandy	Siliceous, mixed	All soils	5	0.08 *(0.01)*
Loamy	Mixed	All soils	3	0.23 *(0.10)*
Coarse-loamy	Mixed	0.33 < VR < 0.50	2	0.18 *(0.00)*
	Mixed	0.05 < KK < 0.20	2	0.32 *(0.01)*
	Mixed	All soils	8	0.32 *(0.12)*
Fine-loamy	Siliceous	All soils	2	0.22 *(0.14)*
	Mixed	0.20 < KK / KH < 0.50	4	0.29 *(0.05)*
	Mixed	0.05 < MT < 0.33	5	0.38 *(0.07)*
	Mixed	All soils	13	0.31 *(0.10)*
Fine-silty	Mixed	MT > 0.33	3	0.42 *(0.09)*
	Mixed	0.20 < VR < 0.50	2	0.38 *(0.04)*
	Mixed	All soils	8	0.43 *(0.08)*
Clayey	Mixed	0.05 < KK / VR < 0.50	3	0.19 *(0.02)*
	Mixed	All soils	5	0.25 *(0.08)*
	Oxidic, kaolinitic	All soils	6	0.18 *(0.04)*
Fine	Montmorillonitic	All soils	8	0.36 *(0.06)*
	Mixed	0.33 < MT < 0.50	2	0.35 *(0.08)*
	Mixed	0.33 < KK / KH < 0.50	4	0.29 *(0.05)*
	Mixed	All soils	13	0.30 *(0.07)*
	Oxidic	All soils	2	0.24 *(0.06)*
Very Fine	Montmorillonitic	All soils	3	0.22 *(0.02)*
	Mixed	All soils	3	0.22 *(0.00)*
Thixotropic	Amorphous	All soils	4	0.28 *(0.08)*

* Approximate weight fraction (X-ray): VR is vermiculite, KK is kaolinite, MT is montmorillonite, and KH is halloysite.
** Numbers in parentheses are standard deviation values.

Part Two

THE LEAM SYSTEM

Rating of Land Characteristics

The relevance of the LEAM system in assessing erodibility of agricultural lands resides on the criteria used to characterize slope hazard, rainfall erosivity risk, and soil erodibility; but, uppermost on the rating itself. Because of the importance of rating in the overall assessment process, several studies describing criteria to rate parameters associated with erosion are first discussed.

Slope Steepness. The soil map of the world indicates 3 dominant slope classes:

(1) 0 to 8%,
(2) 8 to 30%, and
(3) > 30% (Arnoldus, 1977).

Hudson (1977) uses slopes of 12, 27, 36, 42, 65%, and higher as criteria to assess land classes from 1 to 6 in humid areas. In the Philippines, slopes of 3, 8, 15, and 25% are assigned classes A through D to denote increasing order of susceptibility to erosion (Higgins, 1977). Mollenhauer (1980) divides slope gradient classes into 5 categories:

(1) 0 to 3%,
(2) 3 to 9%,
(3) 9 to 17%,
(4) 17 to 36%, and
(5) 36 to 58%.

Rainfall Erosivity. Arnoldus (1980) uses the Modified Fournier's Index (RI) to compile erosivity maps for east and central Africa. Erosivity isolines using RI values of 10, 50, 100, 200, 500, 1000, 1500, and higher were used to develop these erosivity maps.

Soil Erodibility. Dangler *et al.* (1976) group erodibility K values into 6 classes:

(1) very low (0 to 0.10),
(2) low (0.10 to 0.20),
(3) moderate (0.20 to 0.30),
(4) moderately high (0.30 to 0.40),
(5) high (0.40 to 0.50), and
(6) very high (> 0.50).

In turn, Pauwels *et al.* (1980) group K values into 4 erodibility classes:

(1) low to very low (< 0.25),
(2) moderate (0.25 to 0.35),
(3) high (0.35 to 0.45), and
(4) very high (> 0.45).

From the relationships developed to describe slope hazard, rainfall erosivity risk, and soil erodibility K (as discussed earlier in Chapter 3 and based on the above review of literature) each land characteristic listed as a LEAM diagnostic criterion in Table 1 can be independently rated into slope hazard (Table 2), rainfall erosivity risk (Table 4), and soil erodibility classes (Table 8).

Establishing the Framework

The framework of LEAM is simple, and is arranged in two categories: **class** and **subclass** (Table 9). The class reflects the degree of potential erosion risk; whereas, the subclass reflects the kinds of limitations within each class. A symbol E2-S1RR4K1, for example, indicates the soil has been placed in erodibility class E2 and subclass S1RR4K1, and has a moderate potential erosion risk. Placement of a soil in class E2 results from the combination of slope hazard, rainfall erosivity risk, and soil erodibility classes (Tables 2, 4 and 8).

Nine subclasses are included in class E1 (Appendix 4). Classes E2, E3, E4, and E5 have 24, 30, 30, and 18 subclasses, respectively. The large number of subclasses in classes E3 and E4 results from the large number of combinations necessary for ranking as the potential erosion risk increases.

Table 8. Soil erodibility (K) ranges used to develop soil erodibility classes.

Soil Erodibility Class	Erodibility Risk	K Range (Dangler *et al.*, 1976)
K1	Very Low	0.00-0.10
K2	Low	0.10-0.20
K3	Moderate	0.20-0.30
K4	Moderately High	0.30-0.40
K5	High	0.40-0.50
K6	Very High	>0.50

One can expect subclasses at each erodibility category to accommodate most situations occurring under field conditions.

Table 9. Framework of the Land Erodibility Assessment Methodology (LEAM).

Erodibility Class	Potential Erosion Risk	Subclass*	Description
E1	Low	S1, RR1-RR3, K1-K3	Lands highly suitable for food crop production with minimum conservation practices.
E2	Moderate	S1, RR4-RR5, K1-K3 S1, RR1-RR3, K4-K6 S2, RR1-RR3, K1-K3	Lands suitable for food crop production with conventional conservation practices.
E3	High	S1, RR4-RR5, K4-K6 S2, RR4-RR5, K1-K3 S2, RR1-RR3, K4-K6 S3, RR1-RR3, K1-K3	Lands suitable for food crop production with special soil erosion control practices.
E4	Very High	S2, RR4-RR5, K4-K6 S3, RR4-RR5, K1-K3 S3, RR1-RR3, K4-K6 S4, RR1-RR3, K1-K3	Lands suitable for food crop production. Agriculture use should be limited to permanent pasture production.
E5	Extremely High	S3, RR4-RR5, K4-K6 S4, RR4-RR5, K1-K6	Lands unsuitable for any kind of conventional type of agricultural production.

* S is slope hazard class, RR is rainfall erosivity class, and K is soil erodibility class. A complete list of subclasses within each class is given in Appendix 4.

Part Three

TESTING OF LEAM

Using Hawaiian and African Soils

Soil survey data of 19 soil series in low rainfall areas (< 1000 mm/year) on Hawaii and Maui islands, and 10 soil series of Mali, West Africa were used to test LEAM (Foote *et al.*, 1972; Sato *et al.*, 1973; TAMS, 1983). On the Island of Hawaii located between 19° and 20° N Lat, most of the soils are used for cattle grazing. However, due to extreme rainfall variability, forage production varies greatly from year to year. On the Island of Maui located between 20° and 21° N Lat, soils of low rainfall areas are used mainly for irrigated sugarcane on nearly level or moderately sloping lowlands, and for pineapple and pasture on steep lands.

Mali is located in West Africa between 10° and 20° N Lat. Agricultural production is strictly conducted under rainfed conditions as about 60% of the country receives less than 400 mm a year. In addition, Mali's soils are extremely poor in nutrients, where 65% of the country's land consists of low organic matter, nutrient-deficient, sandy soils. About 15% of the land is considered arable, but only 2% is currently under agricultural production (TAMS, 1983).

The erodibility assessment at the soil series category may include soils that meet the requirements of the soil series, but have different erodibility. To prevent this situation, soils of one series that differed in both texture of the soil surface and in slope steepness were divided into phases. This was done to quantify potential erosion risk of several phases within a given soil series.

Monthly rainfall data were obtained from meteorological stations located near each soil series (Appendix 5). To illustrate the differences in rainfall patterns, rainfall data of two representative soils from Hawaii and Mali are shown in Figures 1 and 2. Table 10 shows the *Soil Taxonomy* classification of soils used to test the LEAM.

Land characteristics along with data in Appendix 5 were used to compute LS and RI according to Equations [2] and [3], and the results are summarized in Table 11. The K values for Hawaii and Maui soils were obtained from SCS (1981); and K values for Mali soils were estimated from soil texture and organic matter properties using a procedure developed by ARS/USDA (*cited by* Mitchell and Bubenzer, 1980). Slope length is not normally available in soil surveys. Therefore, for this study, and to permit computation of LS, all soils were assumed to have a slope length of 50 m.

Developing a Computer Program

Using a Statistical Analysis System (SAS) program (SAS, 1982), an Expert System computer program (Appendix 6) was developed to *(i)* first, compute LS and RI; and *(ii)*, then match values of

LS, RI, and K with the diagnostic criteria developed for slope hazard (S), rainfall erosivity risk (RR), and soil erodibility (K) (*see* Tables 2, 4, and 8). Results from these matchings were used to place each soil into the LEAM framework (Table 9). The notation used in the computer program is given in Appendix 7.

The SAS program was used because it provides the tools needed for this kind of expert system development. The SAS program has two steps: the DATA STEP and the PROC STEP. The DATA STEP begins with the introduction of soil and climatic data into a SAS data set. Once the

Table 10. Classification of the Hawaii and Mali soils.

Soil Series	Soil Classification
Island of Hawaii	
Apakuie	Medial over cindery isomesic Typic Vitrandepts
Hanipoe	Medial isomesic Typic Dystrandepts
Hawi	Fine, halloysitic isohyperthermic Typic Ustropepts
Kawaihae	Medial, ashy isohyperthermic Ustollic Camborthids
Kilohana	Medial isomesic Mollic Vitrandepts
Pakini	Medial isohyperthermic Typic Eutrandepts
Naalehu	Medial isohyperthermic Typic Eutrandepts
Puu pa	Medial over fragmental isothermic Ustollic Eutrandpets
Waimea	Medial isothermic Typic Eutrandepts
Island of Maui	
Halimaii	Fine, kaolinitic isothermic Typic Gibbsihumox
Iao	Fine, kaolinitic isohyperthermic Typic Haplustox
Kahana	Clayey, kaolinitic isothermic Tropeptic Haplustox
Keahua	Clayey, kaolinitic isohyperthermic Typic Torrox
Lahaina	Clayey, kaolinitic isohyperthermic Typic Torrox
Kula	Medial isothermic Typic Eutrandepts
Makena	Coarse-loamy, ashy isohyperthermic Aridic Haplustolls
Paia	Fine, kaolinitic isohyperthermic Typic Haplustolls
Wahikuli	Clayey, kaolinitic isohyperthermic Tropeptic Haplustolls
Republic of Mali	
D2	Typic Torripsamments
D5	Psammentic Haplargids
DA2	Typic Haplargids
DA4	Ustalfic Haplargids
PL6	Ultic/Typic Haplustalfs
PL10	Plinthic Haplustalfs
TC4	Typic Cuirustalfs
PL11	Oxic Haplustults
PL13	Oxic Haplustults

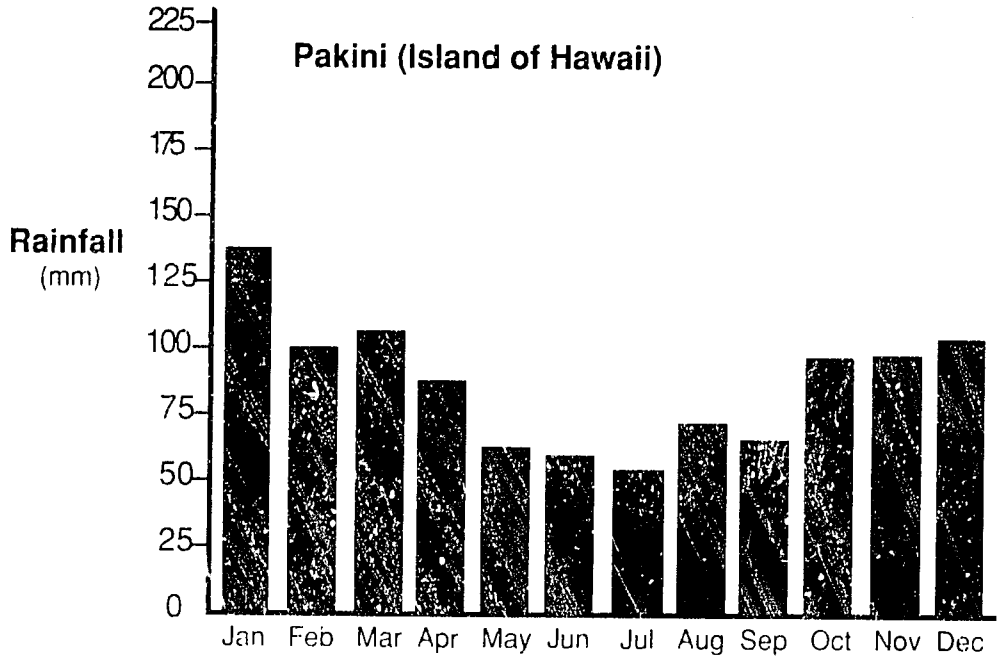


Figure 1. Rainfall distribution of the Pakini soil (Hawaii, USA).

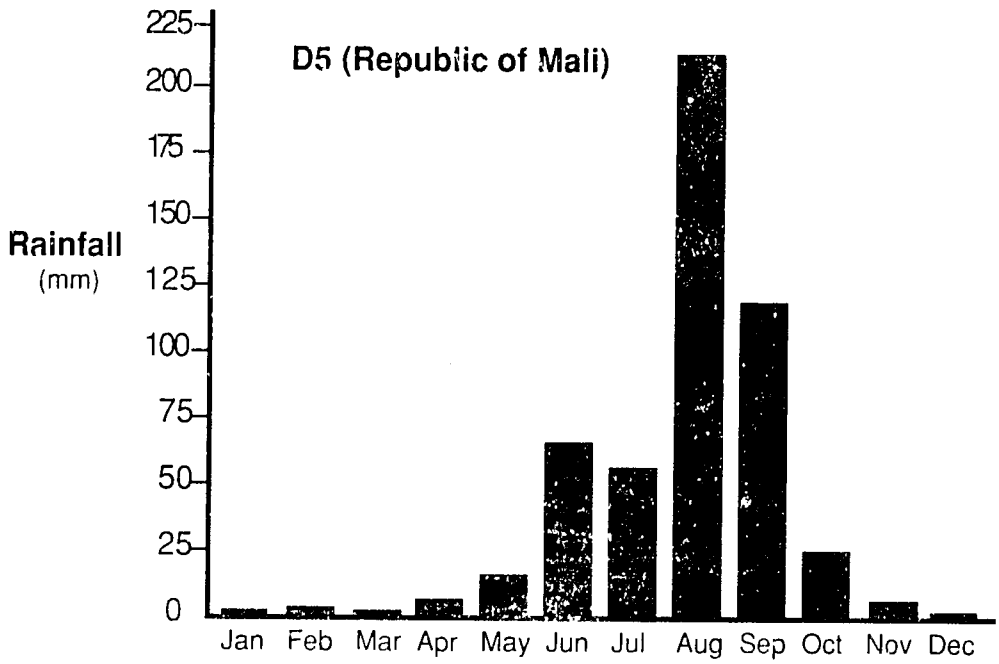


Figure 2. Rainfall distribution of the D5 soil (Republic of Mali).

SAS data set is created, the SAS system is able to produce new SAS data sets from existing ones according to the data statements. The following is an example.

IF RI < 50 THEN CLASS_RR = 1;

The above data statement creates a new SAS data with data meeting those requirements. The SAS system returns afterwards to the initial statement, ready to follow the next instruction. This procedure continues until all data statements have been executed. It should be pointed out that the diagnostic criteria developed for slope hazard, rainfall erosivity risk, and soil erodibility are actually represented in the SAS program by one or several data statements.

In the PROC STEP, the SAS program conducts certain function stated in the PROC statement. For example, PROC PRINT; VAR SOIL TAXA LAND_E CLASS_S CLASS_RR CLASS_K commands the SAS system to match the input data with the diagnostic criteria for each land characteristic and also to print a list of output values such as LAND_E, CLASS_S, and so forth.

Sensitivity Analysis

Erodibility assessments of Oxisols and Inceptisols on Maui were compared with the USLE soil loss (A) values to test the accuracy of LEAM. Soil loss was computed according to Equation [1]. Rainfall erosivity (R) values of meteorological stations located near each soil were obtained from Giambelluca *et al.* (1986) and Roose (1980). Crop management (C) and conservation practice (P) values used in the USLE computation were 0.1 and 1.0, respectively.

Part Four

RESULTS

Most of the Hawaii soils used to test LEAM were Inceptisols, Oxisols, Mollisols, and Aridisols (Table 10). Inceptisols and Oxisols had K values of 0.17 (Table 11). Mollisols and Aridisols had K values of 0.28 or more. On Hawaii and Maui, respectively, 45% and 57% of the soils had slopes greater than 10%. The Mali soils studied were Aridisols, Alfisols, Ultisols, and Entisols (Table 10). The K values ranged from 0.05 to 0.12 for Entisols and Aridisols; Alfisols and Ultisols had K values higher than 0.27. Most of Mali's soils had slopes smaller than 10% (Table 11).

Erodibility Assessments

Soils of Hawaii. On Hawaii and Maui islands, slope steepness is the main factor determining placement of the soils into different erodibility classes (Table 11). Except for extreme cases, such as the Kawaihae and Pakini soils, K values are relatively uniform among soils; hence, their contribution to the overall erodibility assessment is virtually constant. By limiting the erodibility assessment to soils receiving less than 1000 mm per year, the Hawaii soils included in this study possess low potential erosion risk due to rainfall, as was expected.

Maui's Oxisols are placed in erodibility classes E1 and E2, and possess low to moderate potential erosion risk (Table 11). These soils have been cropped with sugarcane for several decades using furrow irrigation. Soil loss occurring in these soils can be attributed to improper water management rather than rainfall erosivity.

Inceptisols on both Hawaii and Maui islands are placed in class E2 or higher, and exhibit moderate to higher potential erosion risks. These soils are found in natural or improved pasture and probably would not experience severe erosion under the prevailing land use. However, a high potential erosion risk exists if the present land use is changed to one that could expose the soil surface to direct raindrop impact. Overall, the erodibility ratings of Oxisols and Inceptisols are consistent with studies that indicate younger soils are more susceptible to erosion than older and highly weathered soils (El-Swaify and Dangler, 1982).

Soils of Mali. Mali's Entisols and Aridisols are placed in class E1 and possess low potential erosion risk (Table 11). These soils are found on nearly level, sandy plains and stabilized sand dunes in the northern, driest area of the country. Ultisols and Alfisols are placed in class E2 or higher. Such placement is the result of high rainfall erosivity risk and/or high soil erodibility. These soils are found on subhumid, nearly level plains which characteristically have plinthite in their lower horizons. In summary, slope steepness is not a major contributing factor to erosion of Mali soils. The degree to which these soils could undergo severe erosion depends primarily upon their intrinsic ability to resist the potential erosivity of

the erratic, short-lived but highly intensive rainfalls of West Africa.

Erodibility Class vs. Soil Loss

Erodibility classes and the estimated soil loss values for Oxisols and Inceptisols on Maui island were compared (Figures 3A,B). The regressions showed r^2 values of 0.86 and 0.90, respectively. The highly significant correlations between erodibility classes and soil loss values illustrate the accuracy with which the LEAM assessed potential erosion risk.

CONCLUSIONS

Erodibility assessments of the soils using LEAM corresponded closely to the estimated USLE soil loss values, indicating that LEAM adequately rates potential erosion risk in quantitative and operational terms. The close agreement between erodibility classes and soil loss values indicates that reliable estimates of potential erosion risk can be obtained by using the LEAM.

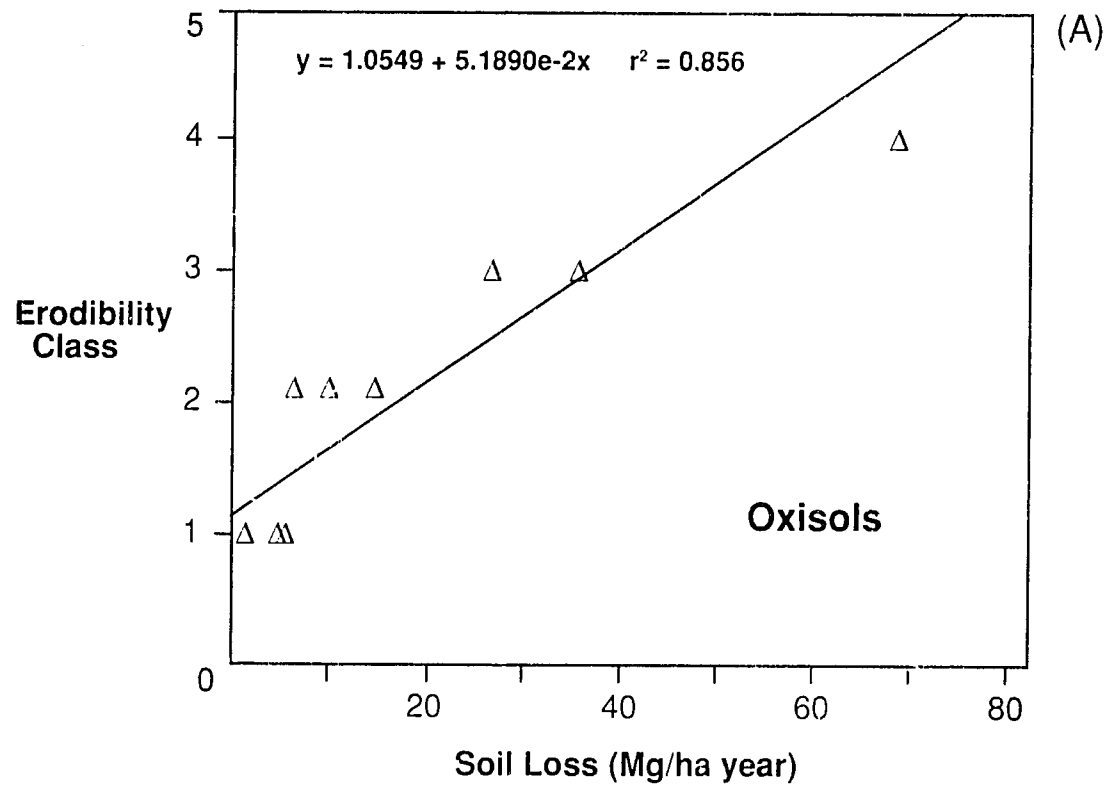
The LEAM is designed to provide quick and reliable estimates of potential erosion risk whenever *Soil Taxonomy* is used in the soil surveys available. To assess potential erosion risk, major land characteristics which are readily obtainable in the soil surveys are selected. The land-rating framework of LEAM provides basic information as to whether a given land has a specific potential erosion risk, and to the limitations associated with land use. It is emphasized that LEAM's erodibility assessments should be regarded as a guide to be eventually replaced by more refined predictive techniques of erosion assessment and control.

Table 11. Soil and site properties and related land

SOIL	PROPERTY		
	Annual Rainfall (mm)	Slope Steepness (%)	Soil Erodibility (K)
Island of Hawaii			
Apakuie	1120	16	0.17
Hanipoe	1120	16	0.17
Hawi	1300	3	0.17
Kawaihae	205	9	0.28
Kilohana	575	16	0.10
Pakini	1056	4	0.43
Naalehu	1183	22	0.17
Puu pa	205	85	0.17
Waimea	674	16	0.17
Island of Maui			
Halimaii	1168	5	0.17
Iao	703	5	0.17
Kahana	1229	5	0.17
Keahua	1168	5	0.17
Kula	851	16	0.17
Kula	851	26	0.17
Lahaina	491	2	0.17
Makena	861	9	0.17
Paia	1274	5	0.17
Wahikuli	491	5	0.17
Republic of Mali			
D2	196	4	0.05
D5	506	4	0.05
DA2	196	4	0.05
DA4	418	4	0.12
PL6	531	1	0.05
PL10	1052	1	0.27
TC4	1118	1	0.38
PL10	1052	1	0.48
PL11	996	1	0.12
PL13	996	1	0.27

'haracteristics used in the erodibility assessment of the Hawaii and Maui soils.

LAND CHARACTERISTIC						ERODIBILITY ASSESSMENT		
Slope Hazard		Rainfall Erosivity		Soil Erodibility		Class	Subclass	Potential Erosion Risk
LS	Rating	RI	Rating	K	Rating			
3.7	S2	114.8	RR3	0.17	K2	E2	S2RR3K2	Moderate
3.7	S2	114.8	RR3	0.17	K2	E2	S2RR3K2	Moderate
0.4	S1	112.8	RR3	0.17	K2	E1	S1RR3K2	Low
1.5	S1	23.3	RR1	0.28	K3	E1	S1RR1K3	Low
3.7	S2	50.0	RR2	0.10	K2	E2	S2RR2K2	Moderate
0.5	S1	92.1	RR2	0.43	K5	E2	S1RR2K5	Moderate
6.3	S4	112.4	RR3	0.17	K2	E4	S4RR3K2	Very High
76.4	S4	23.3	RR1	0.17	K2	E4	S4RR1K2	Very High
3.7	S2	64.5	RR2	0.17	K2	E2	S2RR2K2	Moderate
0.7	S1	129.2	RR3	0.17	K2	E1	S1RR3K2	Low
0.7	S1	82.8	RR2	0.17	K2	E1	S1RR2K2	Low
0.7	S1	121.1	RR3	0.17	K2	E1	S1RR3K2	Low
0.7	S1	129.2	RR3	0.17	K2	E1	S1RR3K2	Low
3.7	S2	79.9	RR2	0.17	K2	E2	S2RR2K2	Moderate
8.5	S4	79.9	RR2	0.17	K2	E4	S4RR2K2	Very High
0.2	S1	62.7	RR2	0.17	K2	E1	S1RR2K2	Low
1.5	S1	77.5	RR2	0.17	K2	E1	S1RR2K2	Low
0.7	S1	113.0	RR3	0.17	K2	E1	S1RR3K2	Low
0.7	S1	62.7	RR2	0.17	K2	E1	S1RR2K2	Low
0.5	S1	59.2	RR2	0.05	K1	E1	S1RR2K1	Low
0.5	S1	135.6	RR3	0.05	K1	E1	S1RR3K1	Low
0.5	S1	59.2	RR2	0.05	K1	E1	S1RR2K1	Low
0.5	S1	115.2	RR3	0.12	K2	E1	S1RR3K2	Low
0.1	S1	128.4	RR3	0.05	K1	E1	S1RR3K1	Low
0.1	S1	215.5	RR4	0.27	K3	E2	S1RR4K3	Moderate
0.1	S1	239.6	RR4	0.38	K4	E3	S1RR4K4	High
0.1	S1	215.5	RR4	0.48	K5	E3	S1RR4K5	High
0.1	S1	191.5	RR3	0.12	K2	E1	S1RR3K2	Low
0.1	S1	191.5	RR3	0.27	K3	E1	S1RR3K3	Low



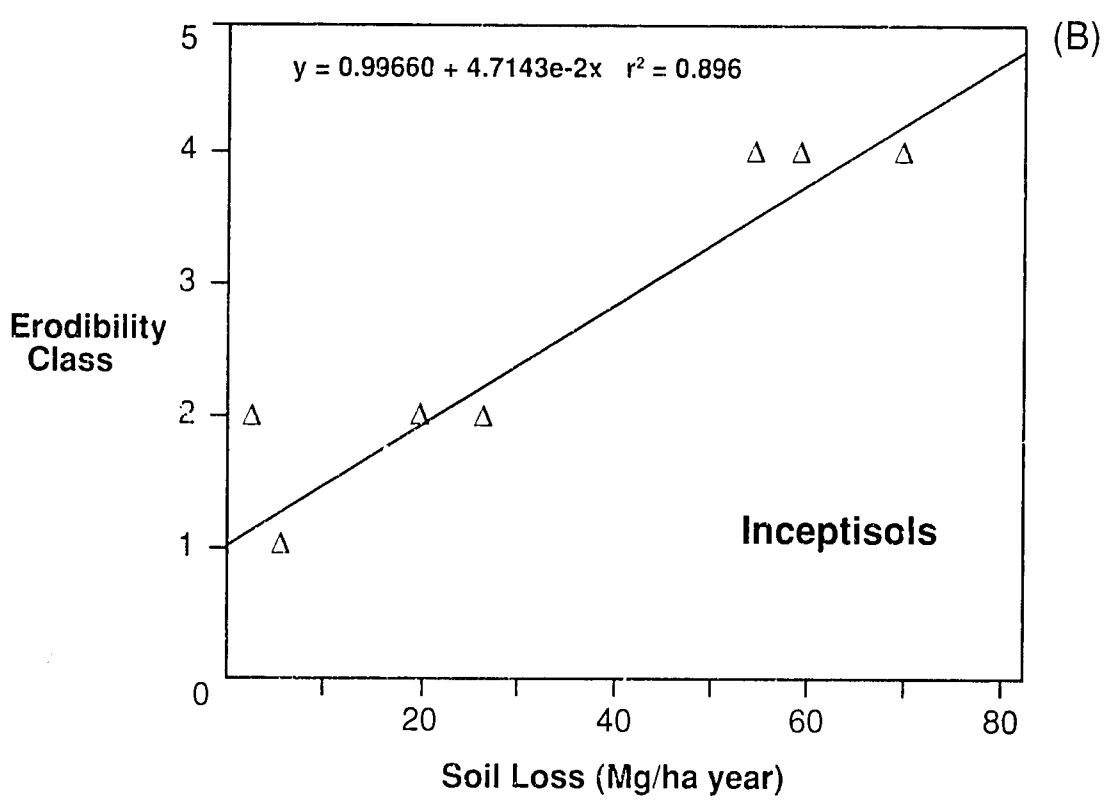


Figure 3. Erodibility classes in relation to the USLE soil loss for *(A)* Oxisols and *(B)* Inceptisols of Maui, Hawaii, USA.

References

Armstrong, C.L., J.K. Mitchell, and F.N. Walker. 1980. Soil loss estimation research in Africa: A review. p. 285-294. *In* M. de Boodt and D. Gabriels (ed.) *Assessment of Erosion*. John Wiley & Sons, Inc., New York, NY.

Arnoldus, H.M.J. 1977. Methodology used to determine the maximum potential average annual loss due to sheet and rill erosion in Morocco. *In* FAO (ed.) *Assessing Soil Degradation*. FAO Soils Bull. 34. FAO, Rome, Italy.

Arnoldus, H.M.J. 1980. An approximation of the rainfall factor in the universal loss equation. p. 127-132. *In* M. de Boodt and D. Gabriels (ed.) *Assessment of Erosion*. John Wiley & Sons, Inc., New York, NY.

Dangler, E.W., S.A. El-Swaify, L.R. Ahuja, and A.P. Barnett. 1976. *Erodibility of Selected Hawaii Soils by Rainfall Simulation*. ARS W-35. ARS/USDA-Univ. of Hawaii Agric. Exp. Stn., Honolulu, HI.

El-Swaify, S.A., and E.W. Dangler. 1982. Rainfall erosion in the tropics: A state of the art. p. 1-25. *In* W. Kussov *et al.* (ed.) *Soil Erosion and Conservation in the Tropics*. Spec. Publ. No. 43. American Society of Agronomy, Madison, WI.

Foote, D.E., E.L. Hill, S. Nakamura, and F. Stephens. 1972. *Soil Survey of the Islands of Kauai, Oahu, Maui, Molokai, and Lanai, State of Hawaii*. SCS/USDA-Univ. of Hawaii, Honolulu, HI.

Giambelluca, T.W., M.A. Nullet, and T.A. Schroeder. 1986. *Rainfall Atlas of Hawaii*. Dept. Land and Natural Resources, Div. Water and Land Development, State of Hawaii, Honolulu, HI.

Hargreaves, G.H. 1977. *World Water for Agriculture (Climate, Precipitation Probabilities and Adequacies for Rainfed Agriculture)*. USAID/Utah State Univ., Logan, UT.

Higgins, G.M. 1977. Land classification. *In* FAO (ed.) *Soil Conservation and Management in Developing Countries*. FAO Soils Bull. 33. FAO, Rome, Italy.

Horn, M.E. 1971. Estimating soil permeability rates. *Proc. ASAE* (IR2): 263-273.

Hudson, N. 1977. Research needs for soil conservation in developing countries. *In* FAO (ed.) *Soil Conservation and Management in Developing Countries*. FAO Soils Bull. 33. FAO, Rome, Italy.

Jaramillo, S., L.A. Manrique, R.B. Bryant, T.W. Scott, B. Name, and J. Jonas. 1985. *Soils and Environmental Conditions of IDIAP Agricultural Research Stations in Panama*. Agronomy

Mimeo. 85-2. Dept. Agron., Cornell Univ., Ithaca, New York, NY.

Lal, R. 1976. Soil erosion on Alfisols in western Nigeria: I. Effects of slope, crop rotation and residue management. *Geoderma* 16: 363-376.

Lal, R., T.L. Lawson, and A.H. Anastase. 1980. Erosivity of rains. p. 143-151. *In* M. de Boodt and D. Gabriels (ed.) *Assessment of Erosion*. John Wiley & Sons, Inc., New York, NY.

Manrique, L.A. 1982. Development of a land suitability classification for potatoes (*Solanum tuberosum* L.). Ph.D. diss. Dept. Agron. and Soil Sci., Univ. of Hawaii, Honolulu, HI.

Mitchell, J.K., and G.D. Bubenzer. 1980. Soil loss estimation. p. 17-62. *In* M.J. Kirby and R.P.C. Morgan (ed.) *Soil Erosion*. John Wiley & Sons, Inc., New York, NY.

Mollenhauer, K. 1980. Land use in water protection areas. p. 271-284. *In* M. de Boodt and D. Gabriels (ed.) *Assessment of Erosion*. John Wiley & Sons, Inc., New York, NY.

Pauwels, J.M., J. Alterman, D. Gabriels, A. Bollinne, and P. Rosseaa. 1980. Soil erodibility map of Belgium. p. 193-201. *In* M. de Boodt and D. Gabriels (ed.) *Assessment of Erosion*. John Wiley & Sons, Inc., New York, NY.

Roose E.J. 1980. Approach to the definition of rain erosivity and soil erodibility in West Africa. p. 153-164. *In* M.J. Kirby and R.P.C. Morgan (ed.) *Soil Erosion*. John Wiley & Sons, Inc., New York, NY.

Sato, H.H., W. Ikeda, R. Paeth, R. Smythe, and M. Takehiro Jr. 1973. *Soil Survey of the Island of Hawaii, State of Hawaii*. SCS/USDA-Univ. of Hawaii, Honolulu, HI.

Soil Conservation Service (SCS). 1951. USDA Agric. Handb. 18. U.S. Government Printing Office, Washington, DC.

Soil Conservation Service (SCS). 1978. *Classification of the Soil Series of the United States*. SCS/USDA. U.S. Government Printing Office, Washington, DC.

Soil Conservation Service (SCS). 1981. *Erosion and Sediment Control: Guide for Hawaii*. SCS/USDA, Honolulu, HI.

Soil Survey Staff. 1975. *Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys*. USDA Agric. Handb. 436. U.S. Government Printing Office, Washington, DC.

Statistical Analysis System (SAS). 1982. *SAS User's Guide*. 1982 edition. SAS Institute, Inc., Raleigh, NC.

Tippets-Abbet-MacCarthy-Stratton (TAMS). 1983. *Mali Land and Water Resources*. Government of Mali/USAID, New York, NY.

Wischmeier, W.H., and J.V. Mannering. 1969. Relation of soil properties to its erodibility. *Soil Sci. Soc. Am. Proc.* 33: 131-137.

Wischmeier, W.H., and D.D. Smith. 1965. *Predicting Rainfall Erosion Losses from Cropland of the Rocky Mountains*. USDA Agric. Handb. 282. U.S. Government Printing Office, Washington, DC.

Wischmeier, W.H., and D.D. Smith. 1978. *Predicting Rainfall Erosion Losses*. USDA Agric. Handb. 537. U.S. Government Printing Office, Washington, DC.

Wischmeier, W.H., C.B. Johnson, and B.V. Cross. 1971. A soil erodibility nomograph for farmland and construction sites. *J. Soil Water Conserv.* 26: 189-192.

Appendices

Appendix 1. Location of the meteorological stations and soil names.

Meteorological Station Name, Location and Soil Name	Latitude	Longitude	Elevation (m)
Hilo, HI, Dysic isohyperthermic, lithic Tropofolist	19°43'S	155° 4'W	11
Alto Tapajos, Brazil, Orthic Ferralsol* (Oxisol)	7°21'S	57°31'W	125
Coari, Brazil, Dystric Gleysol*	4° 5'S	63° 8'W	48
Ponape, USA, not determined	6°58'N	158°13'W	46
Curitiba, Brazil, clayey, kaolinitic thermic, Typic Haplohumult	21°23'S	49°10'W	908
Olinda, Brazil, clayey, oxidic isohyperthermic Rhodic Paleudult	8° 9'S	34°55'W	10
Charleston, SC, fine-loamy siliceous, thermic Aquic Paleudult	32°54'N	80° 2'W	15
Olympia, WA, Brown Podzolic**	46°58'N	122°54'W	61
Aracaju, Brazil, clayey, mixed isohyperthermic Plinthic Paleustult	10°55'S	37° 3'W	6
Rio de Janeiro, Brazil, clayey, kaolinitic Oxic Haplustalf*	22°54'S	43°10'W	27
Brownsville, TX, fine-silty, mixed, hyperthermic Fluventic Haplustoll	25°54'N	97°26'W	6
Lihue, HI, clayey, kaolinitic isohyperthermic Tropeptic Eutrustox	21°59'N	159°21'W	45
San Antonio, TX, fine, montmorillonitic, thermic Petrocalcic Paleustoll	29°32'N	99°28'W	242
Bechar, Algeria, not determined	31°38'S	2°15'W	806
La Rioja, Argentina, Haplic Xerosol*	29°23'S	66°49'W	430
El Paso, TX, loamy-skeletal, mixed, thermic Typic Paleorthid	31°48'N	106°24'W	1194
Honolulu, HI, fine, kaolinitic isohyperthermic Aridic Haplustoll	21°21'N	157°56'W	5
Luanda, Angola, not determined	8°51'S	13°14'E	70

* Food and Agriculture Organization (FAO) soil names.
** U.S. Soil Classification System (1938).

Appendix 2. Moisture availability index (MAI) values for different meteorological stations.

Station*	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Hilo (PE)	1.14	1.75	1.55	1.55	1.23	0.93	1.30	1.39	1.09	1.51	2.66	2.28
Alto Tapajos (PE)	3.12	3.02	2.92	2.06	0.59	0.09	0	0.03	0.75	1.22	2.01	2.40
Coari (PE)	1.92	1.72	1.72	1.91	1.52	0.77	0.25	0.31	0.49	0.74	1.02	1.26
Ponape (PE)	1.56	1.22	1.72	2.35	2.93	2.45	2.24	1.99	2.25	2.28	2.32	2.60
Curitiba (UD)	1.16	0.97	0.74	0.55	0.55	0.77	0.48	0.44	0.88	0.87	0.51	0.86
Olinda (UD)	0.08	0.14	0.49	0.90	1.55	1.73	1.20	0.65	0.21	0.09	0.06	0.06
Charleston (UD)	0.66	0.65	0.46	0.29	0.26	0.39	0.70	0.60	0.50	0.18	0.44	0.68
Olympia (UD)	6.72	4.22	1.86	0.46	0.22	0.07	0.03	0.06	0.28	1.78	3.91	9.52
Aracaju (US)	0.06	0.10	0.29	0.61	1.28	0.95	1.15	0.55	0.21	0.09	0.04	0.06
Rio de Janeiro (US)	0.46	0.40	0.49	0.63	0.43	0.25	0.23	0.16	0.30	0.36	0.45	0.57
Brownsville (US)	0.12	0.12	0.08	0.08	0.11	0.07	0.05	0.12	0.33	0.26	0.15	0.14
Lihue (US)	0.60	0.59	0.49	0.32	0.20	0.14	0.18	0.21	0.18	0.40	0.59	0.81
San Antonio (US)	0.25	0.21	0.14	0.23	0.26	0.13	0.06	0.08	0.15	0.10	0.18	0.28
Bechar (XE)	0	0	0	0	0	0	0	0	0	0.01	0.01	0.02
La Rioja (XE)	0.12	0.14	0.23	0.01	0.01	0	0	0	0	0.01	0.05	0.11
El Paso (AR)	0.05	0.03	0.01	0	0	0.01	0.07	0.07	0.01	0.05	0	0.05
Honolulu (AR)	0.24	0.25	0.10	0.04	0.05	0.01	0.02	0.03	0.05	0.10	0.13	0.25
Luanda (AR)	0.01	0.03	0.11	0.44	0.01	0	0	0	0	0.01	0.05	0.02

Source: Hargreaves, 1977.

* PE is perudic, UD is udic, US is ustic, XE is xeric, and AR is aridic.

Appendix 3. Soil erodibility K values for selected soils.

Number*	Soil Name	K value
1	Typic Argiustoll, fine montmorillonitic	0.39
2	Aquic Argiudoll, fine montmorillonitic	0.30
3	Aridic Argiboroll, fine montmorillonitic	0.26
4	Udic Argiustoll, clayey-skeletal montmorillonitic	0.32
5	Udic Natriboroll, fine-loamy mixed (?)**	0.16
6	Hydric Dystrandept, thixotropic	0.20
7	Typic Umbraquult, fine-loamy siliceous	0.12
8	Histic Humaquept, fine illitic	0.22
9	Ultic Hapludalf, fine-silty mixed (?)	0.52
10	Andic Dystrochrept, thixotropic	0.25
11	Aeric Glossaqualf, fine-silty mixed (?)	0.34
12	Mollic Haploxeralf, fine-loamy mixed (?)	0.13
13	Typic Rhodoxeralf, very fine mixed (VR2,MT2)	0.22
14	Ultic Hapludalf, fine-silty motmorillonitic	0.52
15	Typic Hapludult, fine mixed (?)	0.36
16	Typic Hapludalf, fine mixed (?)	0.40
17	Typic Argiaquoll, fine mixed (?)	0.28
18	Typic Argiboroll, fine-loamy mixed(?)	0.36
19	Psammentic Hapludalf, coarse-loamy mixed (?)	0.50
20	Typic Albaqualf, fine mixed (?)	0.30
21	Plinthic Paleudult, fine-loamy siliceous	0.32
22	Typic Agrudalf, fine-silty mixed (VR- ,MI4)	0.41
23	Borollic Natrargid, fine montmorillonitic	0.38
24	Typic Natraqualf, fine-silty mixed (?)	0.51
25	Typic Haplorthod, coarse-loamy mixed (?)	0.28
26	Typic Fragiorthod, coarse-loamy mixed (VR4)	0.18
27	Cryic Placohumod, thixotropic	0.39
29	Typic Dystrochrept, fine-silty mixed (VR3)	0.35
33	Tropeptic Haplorthox, clayey oxidic	0.17
31	Typic Camborthid, loamy-skeletal, mixed (MI3)	0.50
32	Typic Acrustox, clayey oxidic	0.15
37	Aridic Calcixeroll, loamy-skeletal carbonatic	0.28
40	Petrocalcic Paleargid, loamy-skeletal mixed (?)	0.44
44	Alfic Haplorthod, coarse-loamy mixed (?)	0.29
51	Typic Paleudalf, very fine vermiculitic	0.38
53	Typic Durixeralf, coarse-loamy mixed (MI3,KK3)	0.48
60	Petrocalcic Paleargid, loamy mixed (MT3)	0.19
61	Typic Calciorthid, sandy mixed (?)	0.08
63	Typic Durorthid, loamy mixed (?)	0.16
64	Typic Paleorthid, loamy mixed (?)	0.35
69	Typic Torripsamment mixed (?)	0.09
70	Typic Ustipsamment mixed (?)	0.09
71	Typic Cryandept thixotropic	0.26
102	Typic Acrorthox, clayey oxidic	0.16
103	Haplic Acrorthox, clayey kaolinitic	0.17

* Pedon number in *Soil Taxonomy's Appendix 4* (Soil Survey Staff, 1975). 000P is pedon number for Panamanian soils (Jaramillo *et al.*, 1985).

** Dominant clay mineral by weight fraction (X-ray). Minerals listed as the following: VR is vermiculite, MT is montmorillonite, MI is mica, KK is kaolinite, KH is halloysite, MV is montmorillonite-vermiculite, and ? means unknown.

Appendix 3. Soil erodibility K values for selected soils—*Continued*

Number*	Soil Name	K value
119	Typic Rhodudult, clayey oxidic	0.17
108	Aeric Haplaquod, clayey oxidic	0.09
41	Typic Salorthid, very-fine montmorillonitic	0.24
55	Typic Palexeralf, fine montmorillonitic	0.44
80	Typic Dystrochrept, fine oxidic	0.20
81	Typic Eutropept, fine mixed (MT4)	0.29
82	Typic Argialboll, fine montmorillonitic	0.38
83	Typic Argiaquoll, fine montmorillonitic	0.39
92	Typic Argiustoll, fine montmorillonitic	0.32
110	Typic Placohumod, sandy siliceous	0.06
112	Typic Albaquult, clayey mixed (?)	0.33
114	Oxic Plinthaquult, clayey mixed (KK5)	0.18
116	Typic Tropohumult, clayey oxidic	0.17
45	Aeric Glossaqualf, fine-silty mixed (MT4)	0.40
118	Typic Hapludult, clayey mixed (VR2)	0.18
120	Typic Tropudult, clayey mixed (VR3)	0.21
121	Typic Haplustult, clayey mixed (?)	0.35
124	Aquentic Chromudert, very fine montmorillonitic	0.21
126	Udic Chromustert, very fine montmorillonitic	0.20
115	Xeric Haplohumult, clayey kaolinitic	0.27
122	Typic Haploxerult, fine-loamy mixed (MT3,VR3)	0.38
54	Typic Natrixeralf, fine-loamy mixed (MT3,KK3)	0.45
56	Typic Durargid, fine mixed (MI3)	0.36
57	Typic Haplargid, fine-loamy mixed (MT3,MI3)	0.28
58	Typic Natrargid, fine-loamy mixed (MT2,MI2)	0.44
59	Typic Paleargid, fine mixed (MT3,MI3,KK3)	0.41
79	Typic Xerochrept, coarse-loamy mixed (VR4,KK3)	0.18
87	Typic Natriboroll, coarse-loamy mixed (MI2,KK2,VR2)	0.31
96	Typic Argixeroll, fine-loamy, mixed (MI4, KK1)	0.28
97	Pachic Calcixeroll, fine-silty mixed (MT5,KK2)	0.35
99	Pachic Haploxeroll, coarse-loamy mixed (MI2,KK2)	0.32
130	Typic Haploxeroll, fine-loamy mixed (KK4,MI3)	0.28
123	Typic Torrert, very fine mixed (MV3)	0.22
003P	Aquic Hapludoll, fine mixed (KK3)	0.33
005P	Aeric Tropaqualf, fine halloysitic	0.28
006P	Aeric Tropaquept, fine mixed (KK4)	0.32
008P	Vertic Haplustalf, very fine mixed (KH3)	0.22
009P	Udic Haplustalf, fine mixed (KK4)	0.23
012P	Typic Humitropept, fine mixed (MT3)	0.15
013P	Oxic Humitropept, clayey-skeletal, mixed (KH3)	0.15
004P	Aquic Hapludoll, fine-loamy mixed (KK3)	0.36
005P	Fluventic Ustropept, fine-loamy mixed (MT3)	0.37
014P	Typic Plinthudult, fine mixed (KK3)	0.27
016P	Typic Tropohumult, fine-loamy mixed (KH3)	0.26
017P	Ultic Tropudalf, fine-loamy mixed (KK4)	0.27

* Pedon number in *Soil Taxonomy's Appendix 4* (Soil Survey Staff, 1975). 000P is pedon number for Panamanian soils (Jaramillo *et al.*, 1985).

** Dominant clay mineral by weight fraction (X-ray). Minerals listed as the following: VR is vermiculite, MT is montmorillonite, MI is mica, KK is kaolinite, KH is halloysite, MV is montmorillonite-vermiculite, and ? means unknown.

Appendix 4. Erodibility classes and subclasses of the LEAM framework.

Erodibility Class	Subclass*					
E1	S1RR1K1	S1RR1K2	S1RR1K3	S1RR2K1	S1RR2K2	S1RR2K3
	S1RR3K1	S1RR3K2	S1RR3K3			
E2	S1RR4K1	S1RR4K2	S1RR4K3	S2RR5K1	S2RR5K2	S2RR5K3
	S1RR1K4	S1RR1K5	S1RR1K6	S1RR2K4	S1RR2K5	S1RR2K6
	S1RR3K4	S1RR3K5	S1RR3K6			
	S2RR1K1	S2RR1K2	S2RR1K3	S2RR2K1	S2RR2K2	S2RR2K3
	S2RR3K1	S2RR3K2	S2RR3K3			
E3	S1RR4K4	S1RR4K5	S1RR4K6	S1RR5K4	S1RR5K5	S1RR5K6
	S2RR4K1	S2RR4K2	S2RR4K3	S2RR5K1	S2RR5K2	S2RR5K3
	S2RR1K4	S2RR1K5	S2RR1K6	S2RR2K4	S2RR2K5	S2RR2K6
	S2RR3K4	S2RR3K5	S2RR3K6			
	S3RR1K1	S3RR1K2	S3RR1K3	S3RR2K1	S3RR2K2	S3RR2K3
	S3RR3K1	S3RR3K2	S3RR3K3			
E4	S2RR4K4	S2RR4K5	S2RR4K6	S2RR5K4	S2RR5K5	S2RR5K6
	S3RR4K1	S3RR4K2	S3RR4K3	S3RR5K1	S3RR5K2	S3RR5K3
	S3RR1K4	S3RR1K5	S3RR1K6	S3RR2K4	S3RR2K5	S3RR2K6
	S3RR3K4	S3RR3K5	S3RR3K6			
	S4RR1K1	S4RR1K2	S4RR1K3	S4RR2K1	S4RR2K2	S4RR2K3
	S4RR3K1	S4RR3K2	S4RR3K3			
E5	S3RR4K4	S3RR4K5	S3RR4K6	S3RR5K4	S3RR5K5	S3RR5K6
	S4RR4K1	S4RR4K2	S4RR4K3	S4RR4K4	S4RR4K5	S4RR4K6
	S4RR5K1	S4RR5K2	S4RR5K3	S4RR5K4	S4RR5K5	S4RR5K6

* S is slope hazard, RR is rainfall erosivity risk, and K is soil erodibility.

Appendix 5. Monthly rainfall data for the Hawaii and Mali soils.

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Island of Hawaii												
Apakuie	115	125	167	118	62	20	41	89	47	75	122	146
Hanipoe	115	125	167	118	62	20	41	89	47	75	122	146
Hawi	132	111	140	125	87	76	103	105	64	83	121	136
Kawaihae	45	22	18	15	14	8	4	9	10	15	16	28
Kilohana	62	58	71	54	53	27	33	37	46	45	39	44
Pakini	137	100	104	88	60	59	55	74	68	93	98	107
Naalehu	165	120	141	88	58	41	45	88	76	95	129	132
Puu pa	45	22	18	15	14	8	4	9	10	15	16	28
Waimea	84	80	84	67	42	21	34	45	29	39	63	82
Island of Maui												
Halimaii	173	154	157	115	53	22	35	50	40	60	123	179
Iao	119	105	92	69	31	9	15	20	17	39	74	104
Kahana	170	125	143	120	71	45	67	64	45	70	129	174
Keahua	173	154	157	115	53	22	35	50	40	60	123	179
Kula	135	96	80	86	51	42	46	51	52	52	57	95
Lahaina	98	67	60	38	19	5	9	13	14	23	52	87
Makena	125	93	85	71	57	49	47	48	70	68	56	86
Paia	138	119	146	124	79	63	87	89	59	88	128	144
Wahikuli	98	67	60	38	19	5	9	13	14	23	52	87
Republic of Mali												
D2	0	0	1	1	3	17	47	89	34	4	0	0
D5	0	1	0	5	17	65	58	215	118	24	2	1
DA2	0	0	1	1	3	17	47	89	34	4	0	0
DA4	0	0	0	1	11	44	118	166	67	11	0	0
PL6	0	0	1	5	24	58	144	186	92	20	0	1
PL10	1	0	4	17	65	141	204	333	213	66	7	1
TC4	1	0	1	12	44	157	246	354	224	71	7	1
PL11	0	2	4	31	66	139	220	285	182	57	8	2
PL13	0	2	4	31	66	139	220	285	182	57	8	2

Appendix 6. An expert system computer program for the LEAM.

```
data one; infile n firstobs=3;
input soil $ s x k mr1 mr2 mr3 mr4 mr5 mr6 mr7 mr8 mr9 mr10
mr11 mr12 ar taxa $ r;
*This is a computer program for LEAM, a land erodibility assessment
methodology developed by Luis A  Manrique, Dept.  Agronomy and Soil
Sci.,Univ.  of Hawaii (V1, 02/88; V2, 03/88; V3, 09/88).  x= slope
length, s= slope steepness, m= constant factor, ri= modified fournier's
index, k= soil erodibility, ar= annual rainfall, mr1-mr12= monthly
rainfall, is= slope factor, r= rainfall factor from usle, a= soil
loss (ton/ha year), a1-a6= soil loss at values of c= 0.05, 0.10,
0.20, 0.30, 0.40, and 0.50, respectively, soil= soil name, taxa=
soil order;
*Computation of ls begins;
if x=.  then x= 50;
if s= 5 or s>5 then m= 0.5;
if s=3 or s>3 and s<5 then m= 0.4;
if s=1 or s>1 and s<3 then m= 0.3;
if s<1 then m= 0.2;
s2= s*s;
ls=(lx/22.13)**m)*(0.065 + 0.045*s + 0.0065*s2);
*Computation of ri begins;
r1=(mr1*mr1)/ar;
r2=(mr2*mr2)/ar;
r3=(mr3*mr3)/ar;
r4=(mr4*mr4)/ar;
r5=(mr5*mr5)/ar;
r6=(mr6*mr6)/ar;
r7=(mr7*mr7)/ar;
r8=(mr8*mr8)/ar;
r9=(mr9*mr9)/ar;
r10=(mr10*mr10)/ar;
r11=(mr11*mr11)/ar;
r12=(mr12*mr12)/ar;
ri=r1+r2+r3+r4+r5+r6+r7+r8+r9+r10+r11+r12;
*Rating of individual land characteristics begins;
if ri<50 then class-rr=1;
if ri=50 or ri> 50 and ri< 100 then class-rr=2;
if ri=100 or ri>100 and ri<200 then class-rr=3;
if ri=200 or ri>200 and ri<300 then class-rr=4;
if ri=300 or ri>300 then class-rr=5;
if ls<2 than class-s=1;
if ls=2 or ls>2 and ls<4 then class-s=2;
if ls=4 or ls>4 and ls<6 then class-s=3;
if ls=6 or ls>6 then class-s=4;
if k<0.10 then class-k=1;
if k=0.10 or k>0.10 and k<0.20 then class-k=2;
if k=0.20 or k>0.20 and k<0.30 then class-k=3;
if k=0.30 or k>0.30 and k<0.40 then class-k=4;
if k=0.40 or k>0.40 and k<0.50 then class-k=5;
if k=0.50 or k>0.50 then class k=6;
```

Appendix 6. An expert system computer program for the LEAM—*Continued*

```
*Erodibility assessment begins;
if class-s=1 and (class-rr=1 or class-rr=2 or class-rr=3)
and (class-k=1 or class-k=2 or class-k=3) then land-e=1;
if class-s=1 and (class-rr=4 or class-rr=5) and (class-k=1
or class-k=2 or class-k=3) then land-e=2;
if class-s=1 and (class-rr=1 or class-rr=2 or class-rr=3)
and (class-k=4 or class-k=5 or class-k=6) then land-e=2;
if class-s=2 and (class-rr=1 or class-rr=2 or class-rr=3)
and (class-k=1 or class-k=2 or class-k=3) then land-e=2;
if class-s=1 and (class-rr=4 or class-rr=5) and (class-k=4
or class-k=5 or class-k=6) then land-e=3;
if class-s=2 and (class-rr=4 or class-rr=5) and (class-k=1
or class-k=2 or class-k=3) then land-e=3;
if class-s=2 and (class-rr=1 or class-rr=2 or class-rr=3)
and (class-k=4 or class-k=5 or class-k=6) then land-e=3;
if class-s=3 and (class-rr=1 or class-rr=2 or class-rr=3)
and (class-k=1 or class-k=2 or class-k=3) then land-e=3;
if class-s=2 and (class-rr=4 or class-rr=5) and (class-k=4
or class-k=5 or class-k=6) then land-e=4;
if class-s=3 and (class-rr=4 or class-rr=5) and (class-k=1
or class-k=2 or class-k=3) then land-e=4;
if class-s=3 and (class-rr=1 or class-rr=2 or class-rr=3)
and (class-k=4 or class-k=5 or class-k=6) then land-e=4;
if class-s=4 and (class-rr=1 or class-rr=2 or class-rr=3)
and (class-k=1 or class-k=2 or class-k=3) than land-e=4;
if class-s=3 and (class-rr=4 or class-rr=5) and (class-k=4
or class-k=5 or class-k=6) then land-e=5;
if class-s=4 and (class-rr=4 or class-rr=5) and (class-k=1
or class-k=2 or class-k=3 or class-k=4 or class-k=5 or
class-k=6) then land-e=5;
if land-e=1 then per='low';
if land-e=2 then per='mod';
if land-e=3 then per='high';
if land-e=4 then per='vhigh';
if land-e=5 then per='chigh';
*Calculation of soil loss begins;
a=r*k*ls*2.2;
*In the calculation of soil loss for a bare soil, it was
assumed that c was equal to 1.0 and p was 1.0. The factor
2.2 converts ton/acre year to ton/ha year.
a1=a*0.05;
a2=a*0.10;
a3=a*0.20;
a4=a*0.30;
a5=a*0.40;
a6=a*0.50;
proc print; var soil taxa land-e class-s class-rr class-k;
//
```

Appendix 7. Notation of abbreviations and terms used in the LEAM expert system computer program.

Code	Description
a	USLE's soil loss
a1-a6	Soil loss at different values of c
ar	Annual rainfall
c	Crop management factor of the USLE
class-k	Class for soil erodibility
class-rr	Class for rainfall erosivity risk
class-s	Class for slope hazard
etp	Potential evapotranspiration
k	Soil erodibility
land-e	Land erodibility class
leam	Land erodibility assessment methodology
ls	Slope factor of the USLE
m	Constant factor used in the computation of ls
mr1-mr12	Monthly rainfall
mai	Moisture availability index
p	Conservation practice factor of the USLE
pd	Dependable rainfall
per	Potential erosion risk (low = low, mod = moderate, high = high vhigh = very high, ehigh = extremely high)
r	Rainfall erosivity factor of the USLE
r1-r12	Partial values of the Modified Fournier's index
ri	Modified Fournier's index
s	Slope steepness
s1rr1k1	Land erodibility subclass
soil	Soil name
sp	Soil permeability
taxa	Soil classification at order category
usle	Universal soil loss equation
x	Slope length