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DETERMINING THE RANGE OF TOLERABLE EROSION

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At least as early as 1620, American farmers and patriots recognized water erosion as a problem and attempted to develop practical ways to protect their soil (35).

During the first two decades of the 20th century the seriousness of erosion was indicated by a number of agricultural leaders (3, 33). Following the publication of significant research findings regarding erosion in Missouri (37) and Texas (12), and an educational campaign by the United States Department of Agriculture under the leadership of H. H. Bennett, the House of Representatives passed the Buchanan Amendment to the Agricultural Appropriation Bill for the fiscal year 1930, appropriating $160,000 for investigations of causes of soil erosion and methods for its control (3). This legislation marked the beginning of a vigorous and expanding program, the course of which is known to farmers and the general public throughout much of the world (3).

In order to measure soil conservation progress and to plan most effectively for the future, it is important to establish a common understanding of basic definitions and assumptions. Therefore a mathematical expression has been developed (53) that provides, by definition, for the permanent protection or improvement of soil resources in accordance with measurable standards, and, by assumption, for the fractional utilization of soil property reserves when needed. Net change from present condition is stated by a definite integral involving soil erosion and soil renewal (or addition) rates with time. The information needed for the solution of this "erosion tolerance equation" is: (*a*) specific inventory of present soil resources, (*b*) expression of essential soil property requirements for the future, (*c*) data on erosion (or wearing away) of soil properties with time, and (*d*) data on renewal (or additions) to soil properties with time. Choice of a particular solution will depend upon economic influences within the erosion range from zero to the upper bound of tolerance.

This paper is a review and analysis of viewpoints and data that may help establish ranges of tolerable erosion for each definable case.

The essential soil property given greatest attention herein is depth of favorable soil material.[2] Other essential soil properties may be treated similarly. Illustrations and estimates emphasize water erosion, but the same approach applies to erosion by other agents.

"NORMAL" OR "GEOLOGIC" EROSION AND ESTIMATED TOLERANCES

In discussing normal soil profiles, Marbut (34) says, "It is readily apparent . . . that the normal profile in any region is found in soils which occupy situations in which the material from which the soil has developed, has lain for a relatively long period of time without subjection to removal by erosion. These soils have reached a relatively advanced state of development in which the forces causing development have had time to produce their normal effect on a given material and where local conditions have either had no inhibiting effect or else that effect has been overcome."

This statement by Marbut seems to indicate that no significant erosion is involved in the development of normal soil profiles. Of course, we know that Marbut was fully aware of geologic processes, including normal or geologic erosion. It is also well known that his concept of normal soils included well-developed soils on sloping land. His reference to the absence of erosion during development of a normal soil, therefore, should probably be interpreted as

[1] Southern Plains Branch, Manhattan, Kansas. Contribution from the Soil and Water Conservation Research Division, Agricultural Research Service, in cooperation with the Kansas Agricultural Experiment Station, Department of Agronomy Contribution No. 899.

[2] Soil material below the rooting depth of perennial native plants would correspond to "earth" as used by the Soil Survey of the United States Department of Agriculture (52).

indicating that he considered geologic erosion as being too slow to be considered significant during the development of a soil on moderate slopes with virgin vegetation.

Bennett *et al.* (4) have indicated that, "Failure to distinguish between the timeless process of *normal erosion* and the rapid action of *accelerated erosion,* resulting from human disturbance of the natural conditions of the land surface, explains in large degree the general failure to recognize the vast difference in the effects of these contrasting types of soil disturbance and removal.... Erosion, normally proceeding under a protective cover of vegetation, goes on so slowly that it probably is beneficial as a rule, seldom harmful in effect."

As expressed by Nikiforoff (38), "Geologic erosion takes care of the removal from the surface of such dying off material as fast as it forms, continuously exposing fresher materials to weathering, thus providing a continuous flow of energy and matter into the zone of pedogenesis."

Apparently similar thinking is represented by the statement of Kellogg (28) that "Through proper cropping systems and soil management practices, erosion of soil should be kept somewhere near the normal rate." Presumably, the basis for this statement is the belief that any reduction of soil depth would constitute some degree of damage to the soil.

EROSION UNDER CLOSE-GROWING VEGETATION

Since special significance has been attached to normal or geologic erosion as a basis for judging the adequacy of erosion control, it is important to consider the likely rate of such soil removal.

Recorded losses from small plots, summarized in table 1, provide some idea of the magnitude of water-erosion rates that may have occurred under native vegetation on land that is now used for agriculture (6, 8, 13, 14, 21–23, 32, 39, 47, 50, 51).

Since these results are not from areas protected by virgin vegetation, some errors could occur. Fires under virgin conditions, for example, might result in more erosion than from protected vegetation. The growth and accumulation of organic residues on and within soil surfaces commonly noted as typical of virgin conditions, would probably, however, provide soil protection that would equal or exceed that provided by introduced species of grasses and legumes.

If this tentative conclusion is accepted, it leads to the generalization that natural erosion on short slopes in the United States covered with a mantle of agricultural soil is less than 1 ton per acre annually, and more commonly is of the order of 0.05 to 0.30 ton per acre. Moreover, relations of erosion to slope and rainfall are not obvious. Uncontrolled variables, including overall vegetative cover and density, and water use, evidently exert a major influence on the measured rates of runoff and erosion. However, if the slope length effect is considered equal to the average for row-cropped land, and if average slope lengths are estimated to be four times the lengths of the runoff-erosion plots, then the estimates or erosion under virgin condition would be doubled, or 0.1 to 0.6 ton per acre annually (49).

Langbein and Schumm (31) concluded that erosion with natural vegetation reaches a maximum with annual rainfall between 10 and 15 inches, because improved vegetation causes a decrease above 15 inches and runoff is rare below 10 inches. The rainfall rates in table 1 are too high to test this conclusion.

WATERSHED EROSION

The rate of discharge of sediments and solubles by streams cannot permanently exceed the rate of change of earth materials into soluble forms or into discrete particles that can be transported by running water. Therefore, in a very general way, the rate of stream discharge from a watershed provides a measure of the lower bound for the rate of all rock weathering plus transport of finely divided earth into the watershed. Accumulations of soil or earth represent the excess of weathering plus influx over chemical and physical removal.

This generalization is of limited usefulness, because it tells nothing about the rate of renewal at a particular point or for a relatively short interval of time.

The fact that under virgin conditions land well suited for agriculture usually is covered with a relatively deep mantle of soil and dense vegetation, would support the hypothesis that such land would be subject to lower rates of erosion and of renewal by weathering of un-

TABLE 1

Soil erosion with close-growing vegetation at several different locations

Location	Soil	Area (*A.*)	Slope		Plant Cover	Annual Precipitation (*in.*)	Years of Record (*number*)	Runoff (*in.*)	Soil Loss	
			%	Length (*ft.*)					*T./A./yr.*	*lb./A./in.**
Columbia, Mo.	Shelby loam	0.01	3.7	91	Bluegrass	40.4	14	4.8	0.34	142
Bethany, Mo.	Shelby loam	0.01	8.0	73	Bluegrass	29.5	10	2.4	0.16	134
		0.01	8.0	73	Alfalfa	29.5	10	2.0	0.15	150
		5.56	9.5	—	Bluegrass pasture	27.8	7	0.45	0.06	266
Blacksburg, Virginia	Dunmore silt loam	0.02	5.0	58	Clover and grass	38.2	4	0.11	0.04	726
		0.02	10.0	58	Clover and grass	38.2	4	0.79	0.07	178
		0.02	15.0	58	Clover and grass	38.2	4	0.03	0.01	667
		0.02	20.0	58	Clover and grass	38.2	4	0.13	0.02	308
		0.02	25.0	58	Clover and grass	38.2	4	0.10	0.01	200
Clarinda, Ia.	Marshall silt loam	0.02	9.0	58	Alfalfa	28.9	10	0.63	0.10	32
		0.02	9.0	58	Bluegrass	28.9	10	0.35	0.03	172
Guthrie, Okla.	Stephensville fine sandy loam	0.01	7.7	73	Bermudagrass, clipped	30.2	11	0.28	0.02	144
		0.01	5.2	73	Bermuda and bluestem, undisturbed	29.5	5	0.01	0.00	—
		0.01	7.7	73	Virgin woodland	30.6	10	0.04	0.01	500
		0.01	5.2	73	Woodland, burned yearly	30.6	10	1.14	0.11	194
La Crosse, Wisconsin	Fayette silt loam	0.01	16.0	73	Bluegrass, protected	33.8	6	1.87	0.09	96
		0.01	16.0	73	Bluegrass, clipped	31.7	5	0.89	0.02	44
Mayaguez, Puerto Rico	Cialitos and Catalina clay	0.014	40.0	52	Various perennial grasses	73.8	9	7.80	1.20	308
		0.014	40.0	52	Tropical kudzu	72.0	3	1.30	0.18	276
	Mucara clay	0.014	62.0	52	Coffee with shade trees and natural ground cover	72.7	7	2.30	0.73	634
Pullman, Wash.	Palouse silt loam	0.02	30.0	73	Perennial grasses, cut for hay	19.8	10	0.19	0.08	842
		0.02	22.0	73	Perennial grasses, cut for hay	20.1	6	0.07	0.01	286
		0.02	22.0	73	Virgin grassland, bunch grasses	20.1	6	0.01	0.00	—
Statesville, North Carolina	Cecil sandy clay loam	0.01	10.0	73	Grass, cut for hay	47.8	8	0.91	0.31	682
		0.01	10.0	73	Virgin forest	46.5	9	0.03	0.002	134
		0.01	10.0	73	Forest, burned semi-annually	46.5	9	5.38	3.08	1146
Temple, Texas	Houston Black clay	0.01	2.0	73	Bermudagrass, clipped	33.1	19	0.40	0.10	500
	Austin clay	0.01	4.0	73	Bermudagrass, clipped	32.5	21	0.10	0.02	400
Tyler, Texas	Kirvin fine sandy loam	0.01	8.7	73	Bermudagrass, clipped	40.7	10	0.41	0.08	390
		0.01	16.5	73	Bermudagrass, clipped	41.5	8	0.11	0.005	90
		0.01	12.5	73	Woodland, protected	40.9	9	0.14	0.05	714
		0.01	12.5	73	Woodland, burned in March	40.9	9	1.07	0.36	672
Zanesville, Ohio	Muskingum silt loam	0.01	12.0	73	Wild grasses and weeds	38.9	9	2.11	0.03	28
		0.01	12.0	73	Bluegrass, fertilized	38.9	9	1.70	0.02	24
		3.57	14.0	—	Bluegrass pasture	38.3	9	5.30	0.10	38
		2.23	14.0	—	Woodland, protected	37.3	9	1.20	0.01	16

* Runoff.

derlying rock than the average of these processes throughout a diverse watershed.

Referring to the entire earth, Branson and Tarr (7) have credited Clarke with data used for the calculation that the total amount of earth material (solid plus solubles) emptied into the sea annually averages 462 tons per square mile, or 0.72 ton per acre. Clarke's analyses of river waters indicated that annually an average of 62 tons per square mile are carried to the oceans in solution (11).

Calculations presented in 1911 by Ramann (40) indicate that central European streams were removing soil at the rate of 1 meter of depth in 33,000 years (that is, 0.18 ton per acre annually). In southern Europe the rate was given as 1 meter in 15,000 years (that is, 0.40 ton per acre annually), and in southern Asia as 1 meter in 5000 years (that is, 1.2 tons per acre annually).

More recently, Menard (36) calculated and summarized some rates of regional erosion in closed systems from the volume of deposits derived from the source regions. The volume of sediment is taken as equal to the volume of rock eroded, "on the assumption that the pore space of the sediments is at least no greater than the volume of material lost from the system by solution." These calculations show that, for the Appalachian region, the past rate during 125 million years averaged 6.2 cm. (0.23 foot) per 1000 years compared to the present rate (from the sediment load of rivers) of 0.8 cm. (0.026 foot) per 1000 years. (A loss of 1 cm. of crystalline rock in 1000 years would amount to approximately 0.12 ton per acre annually.) Similar calculations for the entire Mississippi drainage basin show a past rate of 4.6 cm. (0.15 foot) per 1000 years during 150 million lion years and 4.2 cm. (0.14 foot) per 1000 years and 4.2 cm. (0.14 foot) per 1000 years as the present rate. A third closed system, the Himalayas–Indian plains–Indian Ocean, shows a past rate of 21 cm. (0.69 foot) per 1000 years during 40 million years, and a present rate of 100 cm. (3.28 feet) or approximately 12 tons per acre annually in comparison to 0.5 ton per acre for the Mississippi Basin. Apparently the mountainous terrain and heavy rainfall of the Himalayas region account for a more rapid rate of removal of surface rock material than do more gently sloping regions.

In comparing present rates of denudation and orogeny, Schumm (45) indicated that for drainage basins averaging 1500 square miles on sedimentary and metamorphic rocks, average denudation rates range from 0.1 to 0.3 foot per 1000 years. This range on an annual basis per acre would be about 0.33 to 1.0 ton, including material in solution.

It is interesting that stream discharge, in most cases, amounts to average rates between 0.1 and 1.0 ton per acre annually for the land in these major watersheds. Of course, these magnitudes tell nothing about soil erosion or renewal rates, or erosion tolerance at a given point on the landscape.

ROCK WEATHERING AND SOIL RENEWAL

In considering the rate at which soil might be formed to replace soil removed by erosion, Bennett (2) quoted Chamberlin's (9) 1909 statement that "Without any pretensions to a close estimate, I should be unwilling to name a mean rate of soil formation greater than 1 foot in 10,000 years on the basis of observations since the glacial period." This estimate would be less than 0.2 ton per acre annually. Apparently it is intended to be an estimate of the rate of rock weathering into favorable soil material.

Weathering, as visualized by Chamberlin, might, therefore, be counted as that process that often determines how much soil we can afford to lose. This process has been defined by Reiche (42) and further by Keller (27) as "the response of the lithosphere at or near its contact (interface or interzone) with the atmosphere, hydrosphere, and biosphere; it is a dynamic segment of the rock cycle which operates at this interzone."

Additional perspective regarding weathering is obtained by attention to geologic time scales. Rankama (41) has even used weathering rate as an aid in checking the age of the earth. On the assumption that all A40 in the atmosphere and hydrosphere is a decay product of K40 in the earth's crust, he has estimated that 6462 kg. per $cm.^2$ of igneous rock has weathered during the 3.5 billion years of the earth's geologic history. In different terms, this is equivalent to an average annual weathering rate of 0.082 ton of igneous rock per acre per year throughout the earth's history.

Isotopic age determinations as summarized by Kulp (30) agree generally (within ±10 per cent) with previous age estimates by other means. They indicate that Cretaceous rocks, as represented in central Texas for example, are between 63 and 135 million years old (these dates are the beginning of the Cenozoic and of the Cretaceous period, respectively).

Apparently these rocks have been above sea level continuously for at least 63 million years. Yet, whereas in some positions little or no residuum has accumulated over the chalk, in other positions many feet of calcareous silt and clay occur, representing colluvial or alluvial deposition as well as weathering in place.

In the case of the Ozark Plateau, the underlying rocks probably are between 300 million and 600 million years of age (30),[3] and the cherty residuum from weathering of limestone and shale is commonly 25 feet to over 150 feet thick (29). An average annual accumulation rate of about 1.1 pounds per acre could account for a depth of 150 feet. The time span involved here, and in all cases involving millions of years, is so great that it is difficult to use the existing soil depth, land form, and average rock-weathering rate as any indication of what might occur during a few thousand years.

Pleistocene glacial and loessial deposits provide a sharp contrast with ancient residuum. Not only is the unconsolidated material often of considerable depth, but time is in thousands rather than in millions of years. By means of radiocarbon dating, the age of a number of deposits in Iowa has been established; these ages range from about 6500 to 8200 years as the time when post-glacial major vegetational and climatic changes occurred in north-central Iowa to ages greater than 29,000 years for Iowan glaciation substages and pre-Iowan deposits (43, 44).

Such dating has added precision to existing knowledge regarding the many feet of unconsolidated glacial and loessial materials that were deposited alternately during a few thousand years of Late Pleistocene time in response to environmental fluctuations. This precision already has aided studies of soil genesis and should assist in establishing directions and rates of change that determine rates of renewal of essential soil properties.

Jackson and Sherman (24) distinguished between "pedochemical weathering," or past and present chemical weathering in the soil, and "geochemical weathering," or that weathering which took place in the parent material before the start of soil formation. They reviewed considerable research on the course of both types of weathering and recognized that not everyone considers rock weathering and soil formation (or weathering) as separate processes.

Soils studies generally place major emphasis on the upper part of the profile, whereas geologic interest often is concentrated on well-consolidated earth materials at some distance below the surface. This may tend toward neglect of the rock weathering zone that provides material for renewal of the subsoil.

A study involving calcareous Cretaceous sedimentary rocks, by Blank *et al.* (5), concentrated special attention on the weathered material below the solum and traced its characteristics down into specific geologic horizons of slightly weathered, well-characterized rock. Such information, including physical, chemical, and mineralogical evidences, would be especially valuable if it could be supported by reliable dating procedures to permit estimation of reasonable future rates of change for soil renewal.

Jenny (25) has defined the parent material of soil as the state of the soil system at the soil formation time zero, or as the initial state of the soil system. He has attempted to introduce measurements of time into soil formation whenever possible. In reviewing various studies on the effects of time, he pointed out that moisture is considered to be the major agent responsible for decay of building materials. Buildings and monuments have persisted in the dry climates of Egypt and Sicily; yet, the same materials in France or England soon reveal signs of decay. Jenny quoted Goodchild (19), who in 1890 calculated initial rates of weathering of four different limestones used for tombstones as requiring from 240 to 500 years to produce 1 inch of weathering. Akimtzev (1) reported a much more rapid rate of accumulation on slab limestone in the Kamenetz fortress in the Ukraine, U.S.S.R. He found a range of depths from 10 to 90 cm., averaging 30 cm. (12 inches), of rend-

[3] It is recognized that these rocks may have been low-lying or covered in part until post-Cretaceous time.

zina soil developed in 230 years (equivalent to about 7.8 tons per acre annually). The possibility that windblown materials may have contributed to this depth of soil does not, however, appear to have been eliminated.

On 30-year-old volcanic-ash soils in the Soufrière District of St. Vincent, British West Indies, Hardy (20) reported average organic matter (2.1 per cent) and nitrogen (0.10 per cent) levels that were comparable to cultivated soils of St. Vincent, from which he concluded that within 10 to 20 years, sterile volcanic ash may give rise to fertile soil under the prevailing circumstances.

Where rock type and environment are known, these varied evidences regarding weathering provide some basis for estimating likely rates of such renewal required to counterbalance erosion.

SURFACE DEPOSITION AND SOIL RENEWAL

Many soils are underlain by an accumulation of unconsolidated earth that, because it may be favorable for soil renewal, constitutes thus a reserve of depth. Such reserves may be residual from weathering of underlying rock, but more often, in the United States at least, favorable reserves of depth represent deposits transported since the beginning of the Pleistocene, approximately 1 million years ago (30). Moreover, deposition is a continuous process with worldwide as well as local implications about which our knowledge is merely sketchy.

It is recognized, as discussed by Joffe (26), that sediments from streams may be either detrimental or beneficial through enrichment of valley lands, advancement of shorelines, and the filling of undesirable swamps. Local enrichment occurs also by the natural shifting of soil downslope within a single field. The soil at each point on the land represents a balance between removal and enrichment by all the forces of erosion and renewal.

Vast deposits of loess throughout the world generally are credited to wind deposition, and damage by wind erosion is recognized as a widespread problem (3, 10). Little is known about the magnitude of deposition by wind under present conditions, although in 1911 the subject was reviewed by Free (17). After noting various estimates and opinions Free concluded that wind deposition over the states west of the Mississippi River (excluding desert) probably was not less than 0.01 inch (approximately 1.5 tons per acre) annually. Presumably it would be reasonable to expect significant deposition east of the Mississippi as well.

On land returned to grass in 1946 in southwestern Kansas, Chepil[4] estimated "that the grass trapped at least one-half inch of aeolian material in approximately 10 years [1946–1956]." This would amount to 8 tons per acre annually.

TOLERANCE STANDARDS ON AGRICULTURAL LAND

Soil-loss tolerance values have been used to check whether physical removal of soil was low enough to be consistent with goals of soil conservation. Establishment of tolerance magnitudes, as stated by Smith and Wischmeier (49), has been largely a matter of judgment.

In Missouri (46, 48), tolerances have been indicated as 4 tons per acre per year for Marshall and Shelby and related soils; 3 tons for Putnam and other claypans; and 2 tons for sloping soils of the Ozarks. In considering these estimates, it was noted that on Shelby, Grundy, and Putnam, a corn-yield loss of 4 bushels per acre was associated with each inch (approximately 150 tons per acre) of surface-soil loss between 0 and 12 inches (48).

Permissible annual soil losses estimated for Iowa were as follows: 6 tons per acre for permeable soil profiles over permeable, unconsolidated materials; 4 tons for soils with slowly permeable subsoils over unconsolidated materials; 1 ton for deep soil on bedrock; and 0.5 ton for shallow soil on bedrock (54).

Van Doren and Bartelli (55) stated that there is little information on which to base "soil-loss factors" (apparently this expression is the same as "permissible soil loss" or "erosion tolerance"). Using available crop-yield reductions per inch of topsoil loss for various soils in relation to yield losses for Tama silt loam, and assuming that a soil loss of 4.5 tons per acre per year would not affect the crop production of Tama silt loam, they suggested soil-loss factors ranging from the 4.5 tons for Tama to 1.5 tons

[4] Unpublished manuscript, "Mechanics of wind erosion and significance as a sediment source," presented at the ARS-SCS Sedimentation Workshop at Panguitch, Utah, September 11–12, 1962.

for Dubuque silt loam (shallow phase) and 1.4 tons for Mexico silt loam (planosol).

In New York, Free (18) calculated from crop-yield recoveries with good soil management that 2 tons per acre is a reasonable annual erosion tolerance for Bath flaggy silt loam.

In the Southwest, a 2-ton-per-acre annual loss has been suggested as an estimated tolerable loss on deep soils of the Blackland Prairies (50).

DISCUSSION AND CONCLUSIONS

It seems appropriate now to consider whether basic information about the range in rates of soil erosion and estimates of soil renewal can be reconciled with suggested magnitudes of permissible soil loss within the framework of the theoretical erosion tolerance equation mentioned earlier.

First, an assumed erosion tolerance of 5 tons per acre per year might be considered. Acceptance of this value would constitute an assumption either (*a*) that the soil has more favorable volume or depth over the land than is needed for the future, or (*b*) that the renewal rate is known to average at least 5 tons per acre annually.

Now, in the case of soils of the temperate region, which are underlain at shallow depths by crystalline rock or cherty residuum or by essentially impervious clay, it seems unlikely that either of the above assumptions can be supported unless the land operator plans such exceptional measures as applications of large quantities of favorable soil material on the surface or intensive modification of the subsoil. Therefore, with conventional practices, 5 tons per acre annually would for many soils be judged excessive.

A maximum renewal rate of about 0.12 ton by weathering of a 90 per cent purity limestone might be estimated, according to Goodchild (19). A maximum of 0.2 ton would be inferred for weathering of "average" rock by Chamberlin's estimate (4, 9). A similar rate, between 0.1 and 0.6 ton, would be estimated from adjusted[5] erosion under close-growing vegetation if a balance were assumed between erosion and renewal.

This illustrates that the establishment of an erosion-tolerance standard is meaningful only for restricted soil and rock conditions and when soil renewal practices are defined. Extreme measures, such as massive applications to the surface, can compensate for extremely heavy erosion. The choice of extreme measures is an economic choice which might be made but which cannot be assumed generally.

In most cases conventional practices which are functions of research and experience operating over time will be used. Conventional practices, therefore, are likely to change, and erosion tolerances should be conceived as quantities based on present knowledge rather than as permanently fixed quantities.

Soil conservation planning cannot be said to meet the standard of "permanent protection or improvement of soil resources" by assuming improved soil-renewal practices in the future. The basis should be net rates of change that can be proved or, if proof is lacking, assumed rates of renewal that are not higher than the average of rational estimates. The higher estimates of renewal should require proof.

Similar reasoning applies to any erosion-tolerance standard. The 6-ton-per-acre standard for permeable soil profiles over permeable unconsolidated material in Iowa should be tested by checking the reserve depth of the available favorable, permeable material and deciding on a time span over which to plan. If, for example, 1000 years is considered a reasonable time and the reserve depth is at least 40 inches, then a 6-ton tolerance is sound even without considering whether the renewal rate is significant.

There is no reason to attach special significance to the fact that average annual erosion of Marshall silt loam at Clarinda, Iowa (a soil which fits the category described) with close-growing vegetation was 0.1 ton per acre (table 1). The much faster rate of erosion is tolerable without destruction of essential soil properties because of the considerable reserve of depth. With nitrogen fertilization this reserve material has given yields comparable to the non-eroded soil (15, 16), indicating an economic choice between nitrogen fertilizer and increased control of erosion.

A convenient procedure to assure permanent conservation while using up a reserve is to base

[5] Adjusted to an average slope length four times that of the control plots, assuming that erosion increases as the square root of length of slope, the same as for row-cropped fallow land (49).

all planning on sub-intervals of time (such as generations) and on fractional exhaustion of the reserve that is available at the beginning of each sub-interval. This will automatically leave a fraction of the reserve for the future.

In contrast, a 3-ton tolerance on the intense claypan soils of Missouri must be based on the assumption that the relatively shallow layer of favorable material (about 16 inches) over the claypan will be renewed at a rate of at least 3 tons per acre annually, since there is presently a deficiency rather than a reserve of favorable depth.

From knowledge of the intractable nature of the claypan and estimation that with conventional practices deposition on the surface is likely to be considerably less than 3 tons per acre annually, this tolerance is judged excessive unless accompanied by unusual soil-renewal practices. One-half ton per acre, on the other hand, might be a reasonable estimate of surface deposition (in excess of removal by crops), including atmospheric dust influx, ground limestone to combat acidity, conventional mineral fertilization, and perhaps some animal manure. Renewal by change of the claypan would be added to this if proven, but should not be assumed in conservation planning.

The fact that the claypan soil may have developed some of its unfavorable properties because of the slowness of normal erosion during its genesis does not alter the conclusion that only a slow erosion rate is tolerable now without unusual renewal measures. Maintenance or improvement by conventional good management is conceivable only if mineral, organic, and mechanical amendments near the surface are protected from rapid removal by erosion.

Precise information on rates of soil renewal for many diverse conditions is lacking. Unless reserves of essential soil properties are present, erosion-tolerance standards should not exceed rates of soil-property renewal that have been proven or that are as low as average estimates from available information. Any tolerance standard represents an assertion that should require proof, because it could be harmful if wrong, whereas a standard below the upper bound of tolerance is not harmful and is consistent with permanent soil protection or improvement.

Inadequate knowledge for achieving rates within the erosion-tolerance range in every practical situation should not be permitted to influence decisions in favor of setting "tolerances" that are higher than can be achieved but which lack validity. The failure of many present "conservation" plans to provide soil protection and renewal consistent with objective erosion-tolerance standards represents a great challenge to both research and action agencies.

SUMMARY

Attention to erosion in the United States was greatly increased about 35 years ago.

Statements by leading soil scientists have suggested that accelerated soil-erosion rates much greater than "normal" or "geologic" erosion should not be tolerated.

Further clarification of erosion tolerance and related concepts has been provided by a mathematical equation developed to assure consistent approaches in research and practice. Within the framework of this expression it is convenient to consider evidences that may determine the range of tolerable erosion for diverse conditions.

Control-plot determinations of erosion with close-growing vegetation at 12 locations in humid regions indicate that normal slope erosion probably was 0.1 to 0.6 ton per acre annually on land suitable for agriculture. It may have been higher on extreme slopes and where rainfall was deficient for vigorous plant growth.

Discharge of major streams is related in a complex manner to soil erosion and renewal in each watershed, providing a measure of the lower bound over long time intervals for all weathering in the watershed plus all influx of earth material removable by erosion. Magnitudes provided by stream-gauging records and calculations of sediments and solubles in the oceans are between 0.1 and 1.0 ton per acre annually for averages of all lands in a number of large watersheds. The average is about 0.5 ton for the Mississippi Basin now and slightly higher throughout geologic history. These discharge rates tell nothing about erosion or renewal for a particular point or time.

Rock weathering as a source of soil renewal in the contact zone with the atmosphere and hydrosphere has been highly variable with time, nature of rock, depth of regolith, and intensity of agents. Some rates may be too slow for de-

termination over historic time. Overall averages have been estimated as about 0.2 ton per acre annually in the central United States. Slower rates apply to crystalline rocks and more rapid rates have been noted on volcanic ash in the humid tropics. Radiocarbon or other dating techniques and improved procedures for measuring rock weathering are providing opportunities for closer estimation of rates and directions of change of rock into favorable soil materials.

Surface deposition over time and over certain regions has provided reserves of favorable soil material that can be used up on a fractional basis without violating accepted definitions of soil conservation. Such deposition continues to operate, resulting in continuous soil renewal, which may be several tons per acre annually near the source but much less at remote locations.

Erosion tolerance standards based on judgment have been used in soil conservation planning, ranging from 0.5 ton to 6 tons per acre annually.

From evidences reviewed and interrelationships expressed by the erosion-tolerance equation, logical deductions lead to conclusions that for soils with large reserves of depth, the judgment tolerances are conservative, whereas for some soils without reserves or with deficiencies of favorable depth, suggested tolerances are clearly excessive unless accompanied by *exceptional soil renewal practices* that cannot be assumed.

In many cases present knowledge is far from adequate for achieving tolerances except by introducing land use and erosion control or renewal practices that are not acceptable to a great many farm operators. This presents a major challenge to soil conservationists either to improve the effectiveness of erosion control or to provide soil-renewal practices that will assure rates of increase in the magnitude of essential soil properties at least equal to the rates at which the same properties are being worn away by erosion.

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