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19 Effects of Soil Erosion on Productivity in the Southwest

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Any discussion of the soil erosion problem in the Southwestern USA must consider the two distinctly different agricultural systems in the area: (i) the irrigated agronomic crop system found on the deep, nearly level, alluvial soils in the valleys, and (ii) the rangeland system found on the gently sloping to steep alluvial fans and mountain slopes. The rangeland soils have a wide range of characteristics but are generally more gravelly, more cobbly, and shallower than the irrigated alluvial soils. Generally, productivity problems resulting from erosion are minimal on the irrigated agronomic crop system and severe on the rangeland vegetation system.

Our objectives are to present historical evidence of soil erosion and its effect on land productivity, based primarily on experience in southern Arizona, and to explain new modeling techniques that we believe should aid in predicting soil erosion and plant productivity on these lands.

19–1 RANGELAND AND IRRIGATED CROPLAND PRODUCTIVITY (PRIOR TO 1900)

The Spanish established agricultural and livestock industries in the Southwest at about the same time that other European nations began colonization along the east coast of the USA. Father Kino, in 1687, travelled the northern frontier of Mexico, which currently includes southern Arizona, southern New Mexico, and west Texas. He later introduced grazing animals and established missions throughout the area. Livestock pro-

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spered on the desert grasslands, and extensive cattle herds grazed the area by 1840.

The Santa Cruz Valley, between Nogales and Tucson, AZ, was described by Bartlett in 1854 (Humphrey, 1958): "We were off this morning (from Tucson). . . and soon entered a thickly wooded valley of mesquite. A ride of nine miles brought us to San Xavier de Bac. . . . A mile farther we stopped in a fine grove of large mesquite trees near the river, where there was plenty of grass. The bottoms (between San Xavier and Tubac) in places were several miles wide . . . and covered with tall, golden colored grass (big sacation grass) . . . divided by a meandering stream a dozen yards wide and as many inches deep, this shaded by cottonwood, willow and mesquite trees" (p. 203) (Fig. 19-1).

Today, the Santa Cruz Valley, between Nogales and Tucson, described so elegantly by Bartlett in 1854, is typified by a channel 95 km long and about 9.5 m wide and 6.1 m deep (Fig. 19-2). If soil weight is assumed to be 1450 kg/m^3, then 8 million t of soil have been removed in the past 100 years. The distance between these Arizona cities represents only a small portion of lowland channel erosion within the Upper Santa Cruz Basin and a minor portion of lowland channel erosion that has occurred in southeastern Arizona.

Historians have assumed that livestock were equally dispersed over the entire area. However, upland water development and fencing began after 1930 (Wagner, 1952). Before 1930, livestock grazing and irrigated agriculture were more likely confined to riparian lowland areas where surface water supplies were available. If this assumption is correct, grazing and irrigated agriculture were limited to about 20% of the land area, or an estimated 1.5 million ha.

Southeastern Arizona is an arid or semiarid region. Could vegetation covering 20% of the area support 1.5 million cattle or 1 animal ha^{-1} yr^{-1} in 1891? Alkali sacation [*Sporobolus airoides* (Torr.)] and big sacaton (*Sporobolus wrightii* Munro ex Scribn.) are coarse perennial bunchgrasses that were widely distributed in alluvial floodplains in the Southwest before 1900 (Hubbell and Gardner, 1950). The soils on these flood plains are enriched alluvial sediments derived from the surrounding mountains. Their textures are usually medium to moderately fine, and they have high organic matter content. Initially, the soils were classified as Haplustolls, but their taxonomic classification was changed to Torrifluvents, because the solum remains dry more than 90 days during the year (Richardson et al., 1979). These soils receive large amounts of floodwaters during the summer, which, combined with their high available water-holding capacity, makes them extremely productive.

The annual, aboveground, net production of alkali and big sacaton ranges from 6000 kg/ha in dry years to 10 000 kg/ha in wet years at a riparian sites in southeastern Arizona and southwest Texas (J. R. Cox, 1982, unpublished data). In wet years, these areas could easily support 1.5 million cattle, but in dry years the same areas could support less than 1 million head.

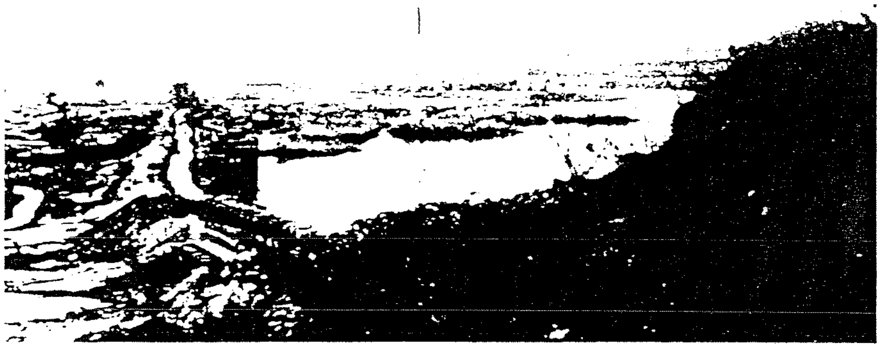

Fig. 19-1. The Santa Cruz River, near Tucson, AZ, before 1900 (Photograph provided by the Arizona Historical Society).

Fig. 19-2. The same area of the Santa Cruz River, near Tucson, AZ, in 1980.

Griffiths (1901), Thornebar (1905), Wooten (1916), and Hubbell and Gardner (1950) concluded that dense sacaton grasslands in lowland riparian areas slowed floodwaters, trapped sediments, and enhanced soil fertility. When sacaton grasslands were plowed, irrigation systems transported water directly from rivers and streams to cropland (Cooke and Reeves, 1976). Following the removal of the sacaton grasslands, either by grazing or farming, there were no barriers to reduce water velocity. Runoff from storms, between 1893 and 1900, entered the lowlands and eroded the soils that produced the forage for the livestock industry. Channel trenching resulted in the lowering of shallow water tables that had irrigated croplands (Griffiths, 1901; Cooke and Reeves, 1976).

Annual precipitation variability is greater in southeastern Arizona than at any other location in the contiguous USA (Hershfield, 1962). Precipitation measurements made 16 km apart also showed wide aereal variability in the same year (Renard and Brakensiek, 1976). Precipitation variability within short distances directly affects upland forage productivity, but, because of runoff accumulation from upland areas in lowland areas (Osborn and Renard, 1973), sacaton grassland riparian areas are expected to have a more stable forage productivity.

19-2 RANGELAND PRODUCTIVITY (1900-1980)

Major soil erosion and vegetation changes occurred in lowland riparian areas between 1893 and 1900. These land changes have had a major effect on land productivity and have necessitated a need for new methods for assessing soil erosion.

The development of railway systems in the Southwest in the latter part of the 19th century allowed stockmen to move large herds of cattle and sheep into the area and provided for rapid distribution of agricultural products (Griffiths, 1901; Bahre, 1977). Humphrey (1958) estimated that 1.5 million cattle grazed in southeastern Arizona by 1891.

Passage of the National Recovery Act, implementation of the Work Progress Administration, and creation of the Civilian Conservation Corps in the 1930s contributed to upland water development and provided fencing to separate grazing units (Cox et al., 1982; Johnsen and Elson, 1979). Livestock, previously concentrated in lowlands, were then redistributed over new grazing lands covering the remaining land area.

Populations of range cattle were relatively stable between 1920 and 1970 and correspond with upland water developments and the continuing processes of providing new grazing areas (Table 19-1). Total cattle in 1980 are generally equivalent to 1910 populations, but more than 50% of the cattle in 1980 were maintained in feedlots, while 99% of the cattle were supported on rangelands in 1910.

In the Southwest, the cyclic wet periods were followed by overstocking, and dry periods were followed by livestock die-offs (Wagner, 1952). With each successive cycle, perennial grass productivity has decreased (Fig. 19-3), shrub densities have increased (Hastings and Turner, 1965) (Fig. 19-4), and cattle populations on rangelands have decreased 87% in 90 years (Table 19-1).

In summary, many factors have contributed to the decrease in rangeland productivity. These factors are conversion of land to agronomic crops, invasion of brush species, grazing practices, channelization, and soil erosion. It is difficult to quantify the magnitude and the interactions of each factor in the overall assessment.

Table 19-1. Cattle populations in southeastern Arizona counties between 1890 and 1980. Populations of range cattle were determined by using published estimates or by subtracting estimated dairy and feedlot cattle from estimated county populations.

	Counties					Cattle populations	
Year	Cochise	Graham	Pima	Pinal	Santa Cruz	Total	Range
	1000 head						
1890						1500†	1500
1900	172	85	98	42	43	400	438
1910	150	98	43	42	44	377	375
1920	84	47	64	45	27	267	263
1930	91	42	88	21	30	272	268
1940	91	33	58	53	26	261	250
1950	65	51	41	38	27	222	210
1960	71	74	83	64	33	325	250
1970	68	60	72	221	24	445	240
1980	67	35	40	207	16	365	188

† Estimate from Humphrey (1958).

19-3 CROPLAND PRODUCTIVITY (1900-1980)

Irrigated agriculture expanded between 1900 and 1960 in southeastern Arizona (Table 19-2), and most of the remaining sacaton grasslands were plowed by 1940. Between 1940 and 1960, irrigated agriculture rapidly expanded to all areas of southern Arizona. Irrigated land use decreased 88% in southeastern Arizona between 1960 and 1980 (primarily due to lowering water table), with an additional 50% decline projected by the year 2020 for the entire state (Arizona Water Commission, 1977). This change has had a major impact on production of cotton (*Gossypium hirsutum* L.) and alfalfa (*Medicago sativa* L.). Differences between 1960 and 1980 show that irrigated farmland has decreased about 1.0 million ha (Table 19-2).

Vegetation on rangeland and abandoned farmland currently consists of widely spaced half-shrubs and shrubs (Cox et al., 1982). Raindrop impact on bare areas between shrubs reduces infiltration and enhances runoff from the shrubland. Runoff, which also comes from roofs and pavement (Fig. 5 and 6), causes downstream flooding (Schulz and Lopez, 1974).

Abandoned farmland has also created a serious wind erosion problem. Dust storms evolving from these lands have caused several highway accidents. Productivity is affected, but at the present the most serious problem is human safety.

19-4 ADVANCES IN TECHNOLOGY FOR PREDICTING EROSION AND PRODUCTION ON RANGELANDS AND CROPLANDS

The rate of soil erosion from upland Arizona rangelands is believed to be significantly less in recent decades than in the early part of this century.

Fig. 19-3. Upland range in the Santa Rita Experimental Range in 1920 (Photograph provided by the Arizona Historical Society).

Fig. 19-4. The same location in the Santa Rita Experimental Range in 1980.

For example, many upland soils had a thin, 3 to 6 cm (or deeper), loamy surface horizon before they eroded. This loamy horizon creates a favorable rooting medium for establishment of plants, particularly desert grasses. During erosion, coarse particles accumulate on the surface. Shaw (1927) identified the coarse particles as erosion pavement, a surface covering of stone, gravel, or coarse soil particles that accumulated as sheet or rill erosion removed the finer soil particles. Lowdermilk and Sundling (1950) suggested that an accumulation of rock fragments on the soil surface was equivalent to soil at similar depths and to layers of uneroded soil found to contain similar amounts of rock fragments. Figure 19-7 is a picture of a typical rangeland soil profile (Hathaway soil) showing the distribution of coarse fragments throughout the profile. Figure 19-8 illustrates the surface condition of a typical rangeland soil with its present erosion pavement.

Table 19-2. Irrigated agriculture in southeastern Arizona between 1900 and 1980, and estimates of abandoned farmland in 1980.

	Counties					
Year	Cochise	Graham	Pima	Pinal	Santa Cruz	Total
	1000 hectares					
1900	2	7	3	5	1	18
1910	2	16	4	10	2	34
1920	5	13	7	12	1	38
1930	153	55	114	31	2	355
1940	368	85	119	240	68	880
1950	145	164	143	353	51	856
1960	258	199	126	300	75	958
1970	37	21	20	105	1	184
1980	36	19	19	90	2	166
Abandoned farmland†	332	180	124	263	73	972

† Abandoned farmland figures were obtained by subtracting 1980 estimates from peak production years.

We suggest that in many rangeland areas the rate of erosion has been stabilized because of the erosion pavement and that a modified range ecosystem now exists. Coarse particles on the surface absorb the impact of raindrops and reduce runoff velocity on the land surface, and thus reduce erosion. Evidence of the effect of erosion pavement on infiltration, as obtained with rainfall simulators, has been mixed. Renard (1970) showed that infiltration increased as the combined cover of shrub, grass, litter, and erosion pavement increased. Tromble et al. (1974) showed an increase in infiltration with rock and gravel on the plot surface. Dadkhah and Gifford (1980) conducted rainfall simulator experiments and simulated compaction effects. As trampling and compaction increased, there was little relationship between rock cover and infiltration rate when erosion pavement ranged from 5 to 10%. Noncompacted or ungrazed soils had increased rock cover, which was associated with increased infiltration. They also reported that rock cover did not have a significant effect on sediment production. However, plot size may have influenced their results (Foster et al., 1981).

Rainfall simulators are not ideal for measuring infiltration and erosion, or for comparing results of different studies, because plot sizes, simulation durations, and simulated rainfall characteristics differ. Erosion pavement may be related to infiltration, as shown in the schematic diagram of Fig. 19-9. Thus, the schematic relationship for a specific soil would be adjusted for the effect of other factors known to affect infiltration and erosion, such as compaction and antecedent moisture.

19-4.1 Rangeland Erosion Pavement and Soil Moisture

Southwestern rangelands are characterized by extreme climatic variability. Certainly, the variability associated with annual, seasonal, spatial, and temporal precipitation is well documented by the work of Renard and

Fig. 5. The village of Tucson, in the Arizona Territory, before 1900 (Photograph provided by the Arizona Historical Society).

Fig. 19–6. The city of Tucson, AZ, in 1980. Note increases in housing density in foreground.

Brakensiek (1976), Osborn (1968), and Osborn et al. (1979). Simulation models have been used to assist with quantification of rainfall variability (Osborn et al., 1979; Osborn et al., 1980a and 1980b; Fogel and Duckstein, 1969; Fogel et al., 1971; Gifford et al., 1967; Smith, 1974; and Smith and Schreiber, 1973 and 1974).

Erosion pavement may also reduce the amount of evaporation from bare soils. Kimball (1973) found that mulches retarded water-vapor movement at the soil-air interface.

Jury and Bellanticoni (1976a and 1976b) found that surface rocks had pronounced effects on both the temperature and water flow. The net vertical heat flow would be either upward or downward in a soil with a rock cover (erosion pavement), depending upon prior conditions. During dry periods a slightly greater amount of moisture was always stored under the

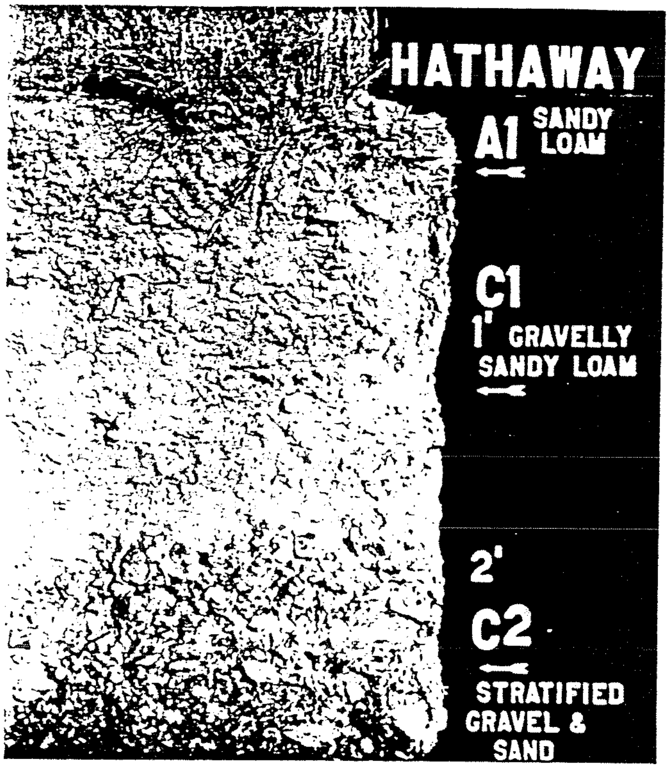

Fig. 19-7. The soil profile for a Hathaway soil containing large amounts of coarse material. Following erosion of the finer particles, the coarse material becomes the erosion pavement.

Fig. 19-8. A typical surface view of the vegetation and erosion pavement on an Arizona rangeland soil.

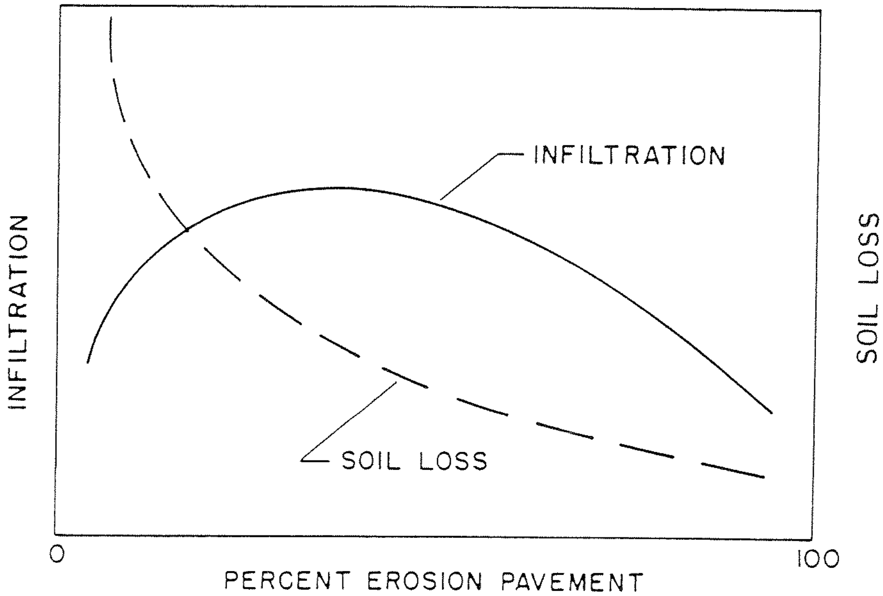

Fig. 19-9. A schematic diagram of the interaction of infiltration and erosion as a function of erosion pavement.

rock compared to adjacent bare soil. Furthermore, the additional soil moisture under the surface rock cover persisted to a depth of 15 cm.

Experimental data to illustrate how soil erosion might affect the productivity of the soil pedon are essentially nonexistent for rangeland areas of the Southwest. Wight and Siddoway (1982) applied the concept of soil loss tolerance (T value), as developed for cropland, to rangelands. They stated that the fragility of rangelands, the irreversibility of erosion damage, and the large margins of error associated with soil loss estimates make it difficult to develop meaningful T values for rangeland. However, a number of recently developed models contribute significantly to our understanding.

19-4.2 Rangeland Forage Production Models

The development of analytical modeling principles associated with digital computers has changed the way much research is conducted. A series of one or more known physically based principles can now be used in a complex problem to conduct a series of numerical experiments (generally a series of mathematical expressions which we call a model), and then to design field experiments with measurements to verify, improve, or calibrate the model (or model coefficients). Thus, a complicated problem can be simplified, eliminating the need for field experiments over all possible conditions. Although quantitative data to substantiate how erosion affects soil productivity are not available for the Southwest, we can use some of the analytical models to arrive at some inferences and to design some experiments to quantify the problem.

Wight and Hanks (1981) predict herbage production using a relationship between vegetation production and precipitation, soil moisture, and climatic variables. The Wight and Hanks yield equation is

$$Y = Y_p (T_a/T_p) \qquad [1]$$

where Y is the actual site yield (kg/ha), Y_p is the potential site yield (kg/ha), T_a is the actual transpiration (mm), and T_p is the potential transpiration (mm). An alternative to this equation is

$$Y = K_e T \qquad [2]$$

where Y is the actual site yield (kg/ha), K_e is the water-use efficiency factor expressed as kg of dry matter produced per kg of water used, and T is the actual transpiration (kg/ha). Lane et al. (1983) discussed the advantages and disadvantages of the method and pointed out that the problems in estimating Y_p and K_e. Values for K_e have often been determined in the greenhouse, so it is not known how this factor applies to the field where water stress, competition among species, spatial variability of soil characteristics, and relative amounts of soil water loss by bare soil evaporation and transpiration are important factors.

An alternative approach to the problem of modeling soil productivity involves more comprehensive water balance models such as the Chemical, Runoff, and Erosion from Agricultural Management Systems (CREAMS) (Knisel, 1980), the Erosion Productivity Impact Calculator (EPIC) (Williams et al., 1983), or the Simulation of Production and Utilization of Rangelands (SPUR) (Wight, 1983). These models are intended for different uses, but they all contain the same algorithms for infiltration (USDA-SCS, 1972) and evapotranspiration (Ritchie, 1972). Evapotranspiration calculations are based on mean daily temperature and solar radiation, soil evaporation based on soil physical properties, and plant transpiration based on a seasonal leaf area index. The evapotranspiration model includes a procedure to reduce computed evaporation and transpiration when soil moisture is limiting, a situation common to arid and semiarid rangeland. Application of algorithms, specifically in the CREAMS model, to arid and semiarid rangeland conditions has been attempted by Lane and Nyhan (1981), Hakonson et al. (1982), and Lane et al. (1983) with considerable success.

Lane et al. (1983) showed prediction accuracy and precision as a function of model complexity (Table 19-3). The simplest model, mean annual net production, obviously does not reflect the annual variability in production, and the confidence interval ranged from 147 to 455 kg/ha. Annual precipitation alone explains 51% of the variance and reduced the width of the confidence interval by 19%. Seasonal estimates of transpiration (estimated by CREAMS) explain 90% of the variance and reduce the confidence interval by 63%. The most significant point with this illustration is that, to reflect production losses due to erosion, detailed measurements

Table 19-3. Summary of regression analysis of predictor variables (x) with standing above ground net biomass of perennial shrubs and grasses (y) at Rock Valley, NV, 1968 and 1971-1976 (Lane et al., 1983).

	Regression equation $y = a + bx$			Summary of predictions		
Predictor	a	b	R^2	% Explained variance[†] 100 R^2	95% CI width[‡] (kg/ha)	% Reduction in 95% CI width[§]
$x = \bar{y}$ = mean	0	1.0	0.0	0	147-455	0
x = annual precip.	−21	2.21	0.51	51	177-425	19
x = seasonal precip.[¶]	136	2.40	0.74	74	211-391	42
x = annual trans.	27	6.94	0.84	84	229-373	53
x = seasonal trans.[¶]	40	9.33	0.90	90	244-358	63

[†] Percent explained variance, or relative improvement over using the mean annual net production as a predictor.

[‡] Width of the 95% confidence interval about the mean annual net production.

[§] Percent reduction in the width of the 95% confidence interval about the mean annual net production.

[¶] Seasonal precipitation and transpiration from January through May.

are required to reflect soil physical and chemical properties as input to a physically based model such as CREAMS.

19-5 CONCLUSION

Past soil losses over the Southwest cannot be estimated accurately. However, upland and lowland arroyo development reductions in livestock population, abandoned farmland acreages, and shrub invasions indicate that land abuse has had a major effect on rangeland and cropland productivity, especially in southeastern Arizona.

Physically based models that describe the important processes known to affect soil productivity have considerable promise for quantifying how erosion affects soil productivity. Furthermore, research planned and conducted in concert with such models can greatly reduce the number of sites necessary to quantify the spatial variability encountered in the rangeland areas of the region.

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