15 Plants for conservation of soil and water in arid ecosystems

H. L. Morton

Arid Land Ecosystems Improvement, Agricultural Research Service, U.S. Department of Agriculture, 2000 E. Allen Rd, Tucson, AZ 85719, USA

Introduction

Soil and water are the critical resources of the world, and they are especially critical in arid and semi-arid regions. Unfortunately they have been squandered through unwise and foolish use. Accelerated soil erosion has been a problem associated with dry land farming and grazing management in semi-arid areas of the world for as long as agriculture has been practiced. Successful ancient cropping practices were able to cope with the problem of soil erosion and lowered fertility mainly through a system of shifting cultivation (Leonard 1973). However increasing population pressure has resulted in grazing and cultivation, for all practical purposes, of all suitable land. Severe droughts, overgrazing, removal of grasses, trees and shrubs have caused severe losses of both soil and water in many regions of the world.

This paper will focus on some of the physical processes involved in soil erosion and water loss and on plants known to be useful for their conservation in arid ecosystems. Additional reviews of soil eriosion by wind and water with descriptions of control measures to which the reader can refer for greater detail are by Bennett (1931), FAO (1960 & 1965), and by Cannell and Weeks (1979).

Most technical problems concerning soil and water conservation have been solved or are solvable with continued research effort. The problems which are not so easily solved are those associated with man. As Perry (1978) points out in his discussion of rangeland resources 'Man is an integral part of all world ecosystems, rangelands are no exception. The future of rangeland resources and their use lies in adaptation and innovation in human aspects of rangeland ecosystems in association with their physical and biological limitations and potentials.'

Plants for conservation of soil

The importance of plants and other biotic factors in the formation of soils is well documented and accepted (Buol *et al.* 1980, Jenny 1980). Soil is formed through processes which require thousands of years, consequently soil is not a renewable resource when viewed from a human perspective. Water plays an important role in soil genesis. It is one of the primary ingredients in the soil forming processes; and, of course, it plays an essential role in the establishment, growth and development of plants and other organisms. Water in the form of rainfall is also responsible for much of the soil erosion in arid regions. Natural erosion is a widespread, centuries-old phenomenon. The deposition of alluvial material has been a key factor in the formation of many productive agricultural and forest soils. Unfortunately, activities of man coupled with natural phenomena such as drought, fire and intense rainfall have caused accelerated soil erosion and degradation of many ecosystems (Cloudsley-Thompson 1977, Cox *et al.* 1983). The importance of plants for the conservation of soil is recognized, has been shown experimentally, but is all too frequently not accepted in practice.

WATER EROSION

The more critical point for watershed managers is how to quantify the loss of soil from water erosion and how important plants are in preventing these losses. A universal soil loss equation has been developed by Wischmeier and Smith (1960) to help in quantifying the problem. The equation is $A=RKCLSP$, where A is the average annual soil loss in tons/ha; R is a rainfall-runoff factor; K is a soil-erodibility factor, C is a crop-management or plant cover factor; L and S are factors for slope length and slope steepness, respectively; and P is a conservation practice factor. Base value for the equation is an average annual loss of soil from tilled continuous fallow, expressed for specific field conditions by the product of the term R, K, L and S. This equation is useful for cultivated fields in more humid areas; however, as Renard (1980) has pointed out, sediment yield from water erosion on rangelands of the western United States (and this is also true of many other arid regions) is larger than might be expected. These high yields are due to: (a) the low density of vegetation which inadequately protects the soil against the erosive forces of raindrops and runoff; (b) steep land slopes and low infiltration, which results in high sheer from the water moving over the land surface; (c) high intensity thunderstorms and their associated high kinetic energy, which leads to excessive splash erosion and overland runoff; and (d) steep channel slopes which contain large amounts of alluvium for transport in the runoff. In the Sahel zone of Africa and most arid areas, the C factor is the most important term in the equation because it varies as a function of cover (Fauck 1977). Most mechanical practices are not suitable to the Sahel, thus, the P factor becomes a constant.

Complete plant cover will effectively control soil erosion as is shown by dense forests and grasslands in more mesic environments. Of the many classes of plants, grasses have been shown to be the most effective vegetative cover for retarding runoff (Connor *et al.* 1930). The ability of a crop to decrease runoff is partially due to its coverage of the soil and partially to its removal of water from the soil and subsequent influence on water infiltration rate.

In Sri Lanka Sandanam and Rasasingham (1982) used a mulch of grass residues at 37.65 tons/ha in a new tea planting with soil slopes of 25 to 39 per cent. They also planted smooth crotalaria, (*Crotalaria pallida (= C. mucronata)*), or weeping lovegrass (*Eragrostis curvula*). Soil losses were lowest on the mulched areas and greatest on those planted with smooth crotalaria. Tea yields were lowest on areas planted to weeping lovegrass and highest on areas with bare soil. During dry periods soil moisture was highest on the mulched areas.

Hoffman *et al.* (1983) using simulated rainfall studied the relationship of soil loss to vegetative ground cover in improved pastures dominated by tall-growing smooth bromegrass (*Bromus inermis*), crested wheatgrass (*Agropyron desertorum*), intermediate wheatgrass (*Elymus hispidus* subsp. *hispidus* (= *A. intermedium*)) and alfalfa (*Medicago sativa*), and on native pastures dominated by low-growing blue grama (*Bouteloua gracilis*) and sedges (*Carex* spp.) and taller growing species, e.g. green needlegrass (*Stipa viridula*), needle-and-thread (*S. comata*) and western wheatgrass (*Agropyron smithii*). In both vegetation types they found that live surface cover estimates were poorly related to runoff and soil loss and adequacy of soil protection can be best estimated by measuring per centage of bare soil.

WIND EROSION

Many arid areas, especially those with sandy, unaggregated soils and sparse vegetation, have a high potential for wind erosion. The wind erosion equation was developed to estimate the annual loss of soil from a given area by wind. The equation may also be used to estimate the physical properties of a soil surface, and vegetation or physical barriers needed to reduce soil loss to acceptable levels under different climatic conditions (Woodruff & Siddoway 1965). The relationship between average annual soil loss and five factors influencing wind erosion is given by: $E=f(I',K',C',L'V)$. E is amount of annual soil loss in tons/ha; I' is a soil erodibility index which depends upon the proportion of soil aggregates greater than 0.84 mm diam. and the slope of the surface; K' is soil surface roughness; C' is the climatic factor which depends on wind velocity and surface soil moisture; L' is unsheltered field length along the direction of the prevailing wind; and V is vegetative cover. The loss of soil for specific conditions can be estimated using the wind erosion equation and values published in tables (Skidmore 1965, Skidmore & Woodruff 1968, Woodruff *et al.* 1972).

SOIL LOSSES FROM WIND

Soil erosion from wind has been estimated by Skidmore and Siddoway (1978) as being a serious problem in many parts of the world and is a problem on 30 million ha in the United States where at least 2 million ha are moderately to severely damaged each year. Chepil (1962) studied the erosive force of wind in wind tunnel experiments and concluded that the most erodible soil particles were about 0.1 mm in equivalent diameter, while particles greater than 0.84 mm in equivalent diameter were nonerodible by most winds. Bagnold (1973) in studies conducted in the Sahara and Chepil (1945) working in the United States showed that most of the eroding material carried by wind remained within 30 cm of the surface, thus, barriers formed by low-growing plants are an effective means of preventing wind erosion.

Scientists on the Jornada Experimental Range, New Mexico marked the soil level on stakes in adjacent honey mesquite (*Prosopis glandulosa*) duneland and grassland areas in 1933 and 1935. Soil levels in these areas were remeasured in 1950 and 1955 and again in 1980 (Gibbens *et al.* 1983). These measurements showed extensive soil movement had occurred on the mesquite duneland site, where, maximum removal and deposition was 64.6 and 86.9 cm, respectively in 1980. On the site partially occupied by mesquite dunes in 1933 there was a net loss of 4.6 cm in soil depth and mesquite dunes had completely occupied the site in 1980. On a transect established across the mesquite-duneland ecotone in 1935, there was a net loss in soil depth of 3.4 cm and mesquite dunes had completely occupied the former grassland in 1980. Gross erosion rates on wind deflated areas were equivalent to 69 tonnes/ha/year on the area of large mesquite dunes and 52 tonnes/ha/year on the area partially occupied by mesquite. At the ecotone transect gross erosion rates were 45, 101, and 40 tonnes/ha/year for the 1935–1950, 1950–1955 and 1955–1980 periods, respectively. The yearly losses probably have little real meaning because in the mesquite dunelands soil loss rates will vary widely between years and in the mesquite dune areas, soils which moved by creep and saltation were trapped by the mesquite plants and remain on site. Therefore, gross soil loss can be best approximated by considering losses on areas of deflation only. The loss of silt and clay through suspension by wind erosion from dunelands could have a major influence on soil properties such as water holding and cation exchange capacities. Loss of silt and clay would also reduce the aggregate stability and soil binding properties imparted by these two size fractions.

PREVENTING WATER AND WIND SOIL EROSION

Numerous studies have shown that establishment of vegetation on degraded lands will improve the structure of the soil, increase infiltration rates and reduce soil erosion D'Egidio *et al.* 1981, Chheda *et al.* 1983, Bridge *et al.* 1983). Thus, revegetation is the only practical, permanent method of conserving soils and restoring productivity on degraded rangeland. At this time even revegetation is not considered to be cost effective for vast areas of the arid lands of the world because of the low yields and the high risks associated with revegetation practices. However, if stabilization of soils in rangelands is not accomplished the degradation will continue. For this reason it is essential that communities which base their economies on livestock reduce their herds to levels which can be supported by the plant resources.

Revegetation of arid lands has not always been successful and the knowledge needed to revegetate is still not adequate for many areas. Cox *et al.* (1982) reviewed the literature concerning the restoration of depleted rangelands in the Chihuahuan and Sonoran deserts of the southwestern United States and northern Mexico. During a 92-year period from 1890 to 1982, more than 300 forb, grass and shrub species and accessions were planted at 400 sites. From these studies 83 species have been recommended, but planting has been successful with these species in only one of ten years. Fourteen species showed greatest adaptation and planting has been successful in one of two or three years with these species. Eleven of the adapted species were introduced perennial grasses: kleingrass (*Panicum coloratum*), blue panicgrass (*P. antidotale*), Lehmann lovegrass (*Eragrostis lehmanniana*), boer lovegrass (*E. curvula* var. *conferta*), Wilman lovegrass (*E. superba*) cochise lovegrass (*E. lehmanniana* X *E. trichophora*), johnsongrass (*Sorghum halepense*), sorghum almum (*Sorghum* X *almum*), yellow bluestem (*Bothriochloa ischaemum* var. *ischaemum*), and buffelgrass (*Cenchris ciliaris*). Two of the adapted species were native perennial grasses: green sprangletop (*Leptochloa dubia*) and sideoats grama (*Bouteloua curtipendula*). One adapted species was a native shrub: fourwing saltbush (*Atriplex canescens*). The most widely adapted species were Lehmann lovegrass and boer lovegrass; however, no species was found to be adapted to all sites within either the Sonoran or Chihuahuan Deserts. However, when the area was divided into reference zones based on elevation, precipitation, number of frost-free and annual growing days, it was possible to identify species which were adapted to a reference zone. Based on these criteria the probability of successful establishment should improve markedly.

Cox and Jordan (1983) planted five Lehmann lovegrass accessions, cochise lovegrass, two boer lovegrass accessions, Wilman lovegrass and blue panicgrass in southeastern Arizona. Their data suggest that germination and emergence of these species follow single or groups of closely spaced rainfall events which deposit 20 mm or more. The probability of this type of summer precipitation total and distribution occurring in southeastern Arizona is one in ten (Smith 1956, Sellers & Hill 1974). This probability is typical of other low rainfall areas in the Chihuahuan Desert (Herbel *et al.* 1973). Thus, a successful rangeland seeding could be expected in only one of ten years. This makes seeding an exceedingly costly practice in the low precipitation areas of the Chihuahuan Desert. If the revegetation effort is to be based only on increased livestock numbers, then revegetation efforts should be discontinued (Jordan 1981). Revegetation based on other environmental considerations, such as soil erosion control, wildlife habitat, water quality, and stability of the watershed may justify the high monetary cost.

Frasier *et al.* (1984) showed that sideoats grama seed emerge during an initial wetting period of from one to five days but will suffer high seedling mortality during a 5-day period following the wet, resulting in less than 35 per cent survival rate. Cochise lovegrass was slower to germinate and less susceptible to the effect of the five-day dry period thus from 40 to 60 per cent of the seedlings survived. This information makes it possible to incorporate probabilistic aspects of precipitation and soil water relations into a description of seedling environment.

One of the most important factors in protecting soil from erosion is plant cover (Rauzi 1960). Gifford and Hawkins (1978), found that heavy livestock grazing reduced infiltration rates by about one-half that found on ungrazed areas, while light grazing reduced infiltration rates to about three-fourths that found on ungrazed areas. They conclude that grazing reduces infiltration and sometimes increases erosion. However, they further point out that grazing influences infiltration and erosion only when the total plant cover has been reduced to some critical level, the plant community is altered to the point where it can no longer produce and maintain mulch or litter cover, and soil structural characteristics have been significantly altered, particularly soil porosity (Orr 1975, Rauzi 1960 & 1963). In northern Australia, Bridge *et al.* (1983) found that heavily grazed pastures containing the legumes stylo (*Stylosanthes hamata*) and alyce clover (*Alysicarpus vaginalis*) had more macropore space and higher infiltration rates in the surface soil than a lightly grazed kangaroo grass (*Themeda triandra* (= *T. australis*)) native grassland.

Grazing lands which have been overgrazed and have reduced infiltration rates can be reclaimed (Orr 1975, Busby & Gifford 1981, Wood & Blackburn 1981) if given protection from grazing. Work in pinyon-juniper (*Pinus edulis–Juniperus osteosperma*) sites in southern Utah by Busby and Gifford (1981) showed that infiltration rates on grazed areas, and infiltration increased as the period of rest from grazing increased. Grazing systems and the intensity of grazing apparently had no effect on infiltration rate in areas which were covered with shrub canopy or in shortgrass interspaces between the shrubs (Wood & Blackburn 1981). However, in the midgrass interspaces grazing influenced infiltration rates, with ungrazed areas having the highest rate (16.5 cm/hr); rested, deferred rotation grazing area next (13.9 cm/hr); grazed, deferred rotation grazing area next (13.1 cm/hr); and heavily stocked continuous grazing having the lowest rate (8.1 cm/hr). In northern Australia, Bridge *et al.* (1983) attributed low hydraulic conductivities to high stocking rates and trampling during the wet season. Wood and Blackburn (1981) suggest that if the plant community and soils have not deteriorated too far, deferred rotation grazing may increase infiltration rate.

Apparently soils will recover from compaction and reduced infiltration rates through exclusion of livestock trampling associated with high grazing intensity (Wood & Blackburn 1981, Busby & Gifford 1981). While measurable improvement in soil macro volume can be measured in one or two years, Orr (1975) found that four years was needed for full recovery of a bluegrass (*Poa pratensis*) pasture in South Dakota and Bridge *et al.* (1983) found that macropore space in stylo pasture increased between the third and fourth wet seasons after establishment.

Black and Siddoway (1971) evaluated tall wheatgrass (*Elymus elongatus* (= *Agropyron elongatum*)) for reduction of wind speed, trapping of snow and protection of soils from wind erosion. Two rows of tall wheatgrass seeded in 90 cm rows

9 or 18 metres apart trapped from 86 to 116 per cent as much water from snow as crop-fallow without barriers. Wind speed at height of 30 cm from leeward of one barrier to windward of the next barrier increased from 17 to 70 per cent of open field in the 9 metre barrier spacing and from 19 to 84 per cent in the 18 metre barrier spacing. They found that short barrier spacing offers more protection on most soils than long barrier spacing when wind deviates from the perpendicular.

Bilbro and Fryrear (1983) found that cotton gin residues applied to the blank rows of two times two sowing pattern increased cotton yields and reduced soil losses. Likewise, a 70 cm wide band of Texas panicum (*Panicum texanum*) also reduced soil losses. A single row of weeping lovegrass or kleingrass formed efficient wind barriers without affecting cotton yields, but sunflower (*Helianthus maximiliani*) reduced cotton yields by 38 per cent and was a less effective wind barrier.

Reclaiming dunelands invaded by woody plants is possible by replacing the invading plants with grasses. In separate studies Gould (1982) and Gibbens (1983) treated honey mesquite in sand-dune areas of New Mexico with 2,4,5-T (2-[2,4,5-trichlorophenoxy]-acetic acid), killing from 48 to 84 per cent of the plants. Herbaceous plants became established on the interdunal areas of the treated sand-dune area, primarily mesa dropseed (*Sporobolus flexuosus*). Gibbens (1983) found that perennial grass production was 7-, 8-, and 4-fold greater on sprayed than on unsprayed areas in the first, second and third years following treatment, respectively. In the fourth year, the unsprayed area received 49 mm more precipitation than the sprayed and production of perennial grass was nearly equal on the two treatments. Gould (1982) found the amount of wind-blown particles during the windy season (February to May) was more than 15-fold greater in the unsprayed area than in the sprayed. Their studies illustrate the critical role played by plants and vegetative cover in preventing soil erosion.

Plants for conservation of water

Growing plants use large quantities of water, especially in arid areas where plants are adept at using water rapidly when it becomes available. With the notable and important exceptions of water harvesting and ground water recharge, to me conservation of water means retention and use of the precipitation where it falls on the land. I would like to briefly discuss why plants can survive in arid areas on naturally occurring precipitation by either escaping or enduring prolonged periods of drought.

DROUGHT ESCAPING PLANTS

Plants which escape drought are those which make adjustments in their life cycles so that they complete vegetative and reproductive development during periods of when moisture is available and become dormant during droughts. Ephemeral annuals such as needle grama (*Bouteloua aristidoides*) survive during drought as seeds. In crop plants the date of planting annual species is adjusted to take advantage of the available moisture and varieties have been developed which mature during the moist period. Perennial species such as buffalo gourd (*Cucurbita foetidissima*) and wild rhubarb (*Rumex hymenosepalus*) have a deciduous growth habit and survive during drought as fleshy roots. While these annual and perennial species are able to conserve water they provide little protection to soil.

DROUGHT ENDURING PLANTS

Plants have several mechanisms which enable them to survive moisture stress. One of the most important is the ability to maintain photosynthesis and growth at low cell-water potential. Mexican palo verde (*Parkinsonia aculeata*) has very small leaflets which are shed when moisture stress is encountered. The leaf rachises and stems contain chlorophyll which continue to produce photosynthate even under moisture stress. Another important mechanism is enhanced water uptake from the soil by an extensive root system. Mesquite, alfalfa and long-lived perennial grasses frequently have extensive root systems. Generally plants growing in arid habitats have higher root to above-ground ratios than plants growing in moist habitats. Another mechanism by which plants endure drought is control of water loss from above-ground parts. This is accomplished by reducing the transpirational area. Creosotebush (*Larrea tridentata*) sheds mature leaves when first exposed to moisture stress because the guard cells are unable to produce movement (Warskow 1965, Hull *et al.* 1971). Immature leaves dry out but are capable of resuming growth when moisture conditions improve. When stress continues, creosotebush sheds newly formed stems and if drought is prolonged branches are also abscissed. As a result of this shedding the mature plant has stems which are typically unbranched, smooth and leafless.

Cacti and other succulents endure drought by living on moisture stored in their tissue. The green stems produce photosynthate and the thick, tough, waxy epidermis prevents moisture loss. Stomata close during periods of moisture stress and the plants are essentially closed. Other plants such as honey mesquite (*Prosopis glandulosa* var. *glandulosa*) do not store large quantities of moisture in their tissue but are able to survive periods of water stress by closing stomata and re-opening stomata during periods of low water stress in order to continue photosynthesis (Haas & Dodd 1972).

The efficient use of precipitation by plants is one of the critical keys to their survival in arid ecosystems. Plants must be able to use water when it is available. If the plant is not able to use water efficiently it will not survive or it will not be as vigorous and productive as other plants. The introduction, establishment, spread and dominance of Lehmann lovegrass on pastures in southern Arizona illustrates this point. Precipitation at a study site on the Santa Rita Experimental Range in southern Arizona occurs in a bimodel pattern with approximately 67 per cent occurring in the summer, and 33 per cent occurring in the winter with dry periods in spring and fall (Green & Martin 1967). The native species occurring in this desert grassland are both warm-season and cool-season grasses; however, the cool-season species were eliminated or drastically reduced in density by heavy grazing pressure from domestic livestock. Consequently, the plants which remain are primarily warm-season species which grow when moisture is available in the summer but are dormant when precipitation falls in the winter. Lehmann lovegrass was introduced into southern Arizona in the 1930s where it has become well established on some pastures. It is a warm-season grass which is relatively more cold tolerant than the native grass species and will begin growing earlier in the spring and continue to grow later in the fall than the native, warm-season grasses (Elmi 1981). Thus, it is capable of exploiting winter precipitation which generally is not used by warm-season species. Table 15.1 shows forage production by Lehmann lovegrass and forage production by all species during a ten year period in which Lehmann lovegrass was invading a site in the Santa Rita Experimental Range, Arizona. Forage production increased more than threefold as the per centage of Lehmann lovegrass in the forage increased from 11 to 93 per cent. This increase in total forage production due to Lehmann lovegrass has been documented at other sites in southern Arizona (Martin & Morton 1980) and it is evident that this species is filling a void in the desert grassland left by the removal of cool-season grasses.

Table 15.1 Forage production by Lehmann lovegrass and all grasses during a ten year period on the Santa Rita Experimental Range, Arizona.

	Forage production (kg/ha)	
Year	Lehmann lovegrass	Total
1972	40	383
1973	38	195
1974	85	242
1975*	–	–
1976	446	664
1977	526	681
1978*	–	–
1979	863	969
1980	798	819
1981	1334	1432

*Forage production not measured because of livestock grazing in pasture.

References

Bennett, H.H. 1931. Problems of soil erosion in the United States. *Ann. Assoc. Am. Geogr.* 21: 147–170.

Bagnold, R.A. 1973. *The physics of blown sand and desert dunes.* London: Butler and Tanner.

Bilbro, J.D. and D.W. Fryrear 1983. Residue management and cultural practices for a semi-arid region. *J. Soil Water Conserv.* 38(3): 312–314.

Black, A.L. and F.H. Siddoway 1971. Tall wheat grass barriers for soil erosion control and water conservation. *J. Soil Water Conserv.* 26: 107–110.

Bridge, B.J., J.J. Mott, W.H. Winter and R.J. Hartigan 1983. Improvement in soil structure resulting from sown pastures on degraded areas in the dry savanna woodlands of northern Australia. *Aust. J. Soil Res.* 21(1): 83–90.

Buol, S.W., F.D. Hole and R.J. McCracken 1980. *Soil genesis and classification.* 2nd edn. Ames: Iowa State University Press.

Busby, R.E. and G.E. Gifford 1981. Effects of livestock grazing on infiltration and erosion rates measured on chained and unchained Pinyon–Juniper sites in southeastern Utah. *J. Range Manag.* 34: 400–405.

Cannell, G.H. and L.V. Weeks 1979. Erosion and its control in semi-arid regions. In *Agriculture in semi-arid environments,* A.E. Hall, G.H. Cannell and H.W. Lawton (eds): 238–256. Berlin: Springer.

Chepil, W.A. 1945. Dynamics of wind erosion: I. Nature of movement of soil by wind. *Soil Sci.* 60: 305–320.

Chepil, W.A. 1962. A compact rotary sieve and the importance of dry sieving in physical soil analysis. *Soil Sci. Soc. Am. Proc.* 26: 4–6.

Chheda, H.R., O. Babalola, M.A.M. Saleem and M.E. Aken'Ova 1983. Sown grassland as an alternative to shifting cultivation in lowland humid tropics. *Proc. XIV Int. Grassland Congr.* Lexington: Kentucky, June 15–24 1981, J.A. Smith and V.W. Hays (eds): 774–777. Boulder, Colorado; Westview Press.

Cloudsley-Thompson, J.L. 1979. *Man and the biology of arid zones.* Madison: University Park Press.

Connor, A.B., R.E. Dickson and D. Scoates 1930. *Factors influencing runoff and soil erosion.* Texas Exp. Sta. Bull. 411.

Cox, J.R. and G.L. Jordan 1983. Density and production of seeded range grasses in southeastern Arizona (1970–1982). *J. Range Manag.* 36(5): 649–652.

Cox, J.R., H.L. Morton, T.N. Johnsen, Jr., G.L. Jordan, S.C. Martin and L.C. Fierro 1982. *Vegetation restoration in the Chihuahuan and Sonoran deserts of North America.* ARM–W–28, Oakland, California: US Dept. Agric., Agric. Res. Serv.

Cox, J.R., H.L. Morton, J.T. LaBaume and K.G. Renard 1983. Reviving Arizona's rangelands. *J. Soil Water Conser.* 38(4): 342–345.

D'Egidio, B.P., L. Nistri and C. Zanchi 1981. Study of runoff, infiltration and soil losses on pasture under different management in the Appenine mountains using a field rainfall simulator. *Annali Ist. Sper. Studio Difesa Suolo, Firenze.* 12: 245–260.

Elmi, A.A. 1981. *Phenology, root growth and root carbohydrates of Lehmann lovegrass (Eragrostis lehmanniana) in response to grazing.* MS Thesis, University of Arizona, Tucson.

Fauck, R. 1977. Soil erosion in the Sahelian zone of Africa: Its control and its effect on agricultural production. In *Int. symp. on rainfed agriculture in semi-arid regions,* G.H. Cannell (ed.). Riverside: University of California.

FAO 1960. *Soil erosion by wind and measures for its control on agricultural lands.* FAO Agric. Dev. Pap. No. 71. Rome: FAO.

FAO 1965. *Soil erosion by water.* FAO Agr. Dev. Pap. No. 81. Rome: FAO.

Frasier, G.W., D.A. Woolhiser and J.R. Cox 1984. Emergence and seedling survival of two warm-season grasses as influenced by the timing of precipitation: A greenhouse study. *J. Range Manag.* 37(1): 7–11.

Gibbens, R.P. 1983. Grass and forb production on sprayed and nonsprayed mesquite (*Prosopis glandulosa* Torr.) dunelands in south-central New Mexico. *Proc. 14th Int. Grassland Congr.*, Lexington: Kentucky, June 15–24 1981, J.A. Smith and V.W. Hays (eds): 437–440. Boulder, Colorado: Westview Press.

Gibbens, R.P., J.M. Tromble, J.T. Hennessy and M. Cardenas 1983. Soil movement in mesquite dunelands and former grasslands of southern New Mexico from 1933 to 1980. *J. Range Manag.* 36(2): 145.

Gifford, G.F. and R.H. Hawkins 1978. Hydrologic impacts of grazing on infiltration ranges – a critical review. *Water Resour. Res.* 14: 305–313.

Gould, W.L. 1982. Wind erosion curtailed by controlling mesquite. *J. Range Manag.* 35(5): 563–566.

Green, C.R. and S.C. Martin 1967. *An evaluation of precipitation, vegetation and related factors on the Santa Rita Experimental Range.* Technical Reports on the meteorology and climatology of arid regions, No. 17. Tucson: Institute of Atmospheric Physics, The University of Arizona.

Haas, R.H. and J.D. Dodd 1972. Water stress patterns in honey mesquite. *Ecology* 53: 674–680.

Herbel, C.H., G.H. Abernathy, C.C. Yarbrough and D.K. Gardner 1973. Rootplowing and seeding arid rangelands in the southwest. *J. Range Manag.* 26: 193–197.

Hoffman, L., R.E. Ries and J.E. Gilley 1983. Relationship of runoff and soil loss to ground cover of native and reclaimed grazing land. *Agron. J.* 75: 599–602.

Hull, H.M., S.J. Shellhorn and R.E. Saunier 1971. Variations in creosotebush (*Larrea tridentata*) epidermis. *J. Ariz. Acad. Sci.* 6: 196–205.

Jenny, H. 1980. *The soil resource, origin and behaviour.* New York: Springer.

Jordan, G.L. 1981. *Range seeding and brush management.* Arizona Agric. Exp. Sta. Bull. No. T81121.

Leonard, J.N. 1973. *The first farmers.* New York: Time-Life Books.

Martin, S.C. and H.L. Morton 1980. Responses of false mesquite, native grasses and forbs and Lehmann lovegrass after spraying with picloram. *J. Range Manag.* 33(2): 104–106.

Orr, H.K. 1975. Recovery from soil compaction on bluegrass range in the black hills. *Trans. Am. Soc. Agric. Engin.* 18: 1076–1081.

Perry, R.A. 1978. Rangeland Resources: worldwide opportunities and challenges. In *Proc. First Int. Rangeland Congr.*, D.N. Hyder (ed.): 7–9. Denver: Soc. Range Manag.

Rauzi, F. 1960. Plant cover increases water intake rate on rangeland soils. *Crops Soils* 12: 30.

Rauzi, F. 1963. Water intake and plant composition as affected by differential grazing on rangeland. *J. Soil Water Conserv.* 18: 114–116.

Renard, K.G. 1980. Estimating erosion and sediment yield from rangeland. *Proc. Symposium on Watershed Manag.* July 21–23 1980: 164–165. Boise, Idaho: ASCE.

Sandanam, S. and C.C. Rasasingham 1982. Effects of mulching and cover crops on soil erosion and yield of young tea. *Tea Q.* 51(1): 21–26.

Sellers, W.D. and R.H. Hill 1974. *Arizona climate (1931–1972).* Tucson: University of Arizona Press.

Skidmore, E.L. 1965. Assessing wind erosion forces: directions and relative magnitudes. *Soil Sci. Soc. Am. Proc.* 29: 587–590.

Skidmore, E.L. and F.H. Siddoway 1978. Crop residue requirements to control wind erosion. In *Crop Residue Management Systems*, Chapter 2, Am. Soc. Agron. Spec. Pub. No. 31.

Skidmore, E.L. and N.P. Woodruff 1968. *Wind erosion forces in the United States and their use in predicting soil loss.* USDA Agr. Handbook No. 346.

Smith, H.V. 1956. *The climate of Arizona.* Arizona Exp. Sta. Bull. No. 279.

Warskow, W.L. 1965. *Factors affecting stomatal opening of creosotebush (Larrea tridentata [DC] Cov.) and their combined effect of herbicide activity.* MS Thesis, Tucson: University of Arizona.

Wischmeier, W.H. and D.D. Smith 1960. A universal soil-loss equation to guide conservation farm planning. *Int. Congr. Soil Sci.*, Vol. II: 418–425.

Wood, M.K. and W.H. Blackburn 1981. Grazing systems: Their influence on infiltration rates in the rolling plains of Texas. *J. Range Manag.* 34: 331–335.

Woodruff, N.P., L. Lyles, F.H. Siddoway and D.W. Fryrear 1972. *How to control wind erosion.* ARS–USDA Agric. Inf. Bull. No. 354.

Woodruff, N.P. and F.H. Siddoway 1965. A wind erosion equation. *Soil Sci. Soc. Am. Proc.* 29: 602–608.