2 The WEPP Model and Its Applicability for Predicting Erosion on Rangelands

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ABSTRACT

The Water Erosion Prediction Project (WEPP) model is intended to replace the Universal Soil Loss Equation for predicting soil erosion. The WEPP is a fundamental process-based model that operates on a daily time step to estimate land, soil and vegetation conditions when a rainfall event occurs, and then uses this information to predict the hydrology and erosion of single events. The WEPP is used in conjunction with an input climate data file, long term estimates are based on the accumulated erosion occurring during the period of record covered by the input climate file. This chapter describes the representation of rangelands for making estimates of the land, soil, and vegetation conditions, and their effect on soil erosion estimates. Additionally, shortcomings and advantages of WEPP for erosion prediction on rangelands is discussed.

The WEPP brings to the natural resource manager a tool for not only the evaluation of the impacts of management on soil erosion, but also for the evaluation of offsite impacts related to management decisions.

The USLE (Universal Soil Loss Equation; Wischmeier & Smith, 1965, 1978) and its revision RUSLE (Revised USLE; Renard et al., 1991) is an erosion prediction technology that has served mankind well. Because of its empirical nature, however, it has proven to be difficult to apply in some cases, particularly to offsite problems. Additionally, the empirical database to support its application to rangelands and to many other situations is very small.

In 1969, Meyer and Wischmeier presented a model of the water erosion process that was more basic in nature. The CREAMS model (Chemicals, Runoff, and Erosion from Agricultural Management Systems; U.S. Department of Agriculture, 1980) included the more fundamental processes of water erosion and sediment transport. A more recent effort was initiated to replace the USLE

Variability of Rangeland Water Erosion Processes, SSSA Special Publication 38.

with fundamental erosion process technologies in a broad based project titled WEPP (Water Erosion Prediction Project; Foster & Lane, 1987; Nearing & Lane, 1989).

The WEPP is expected to be ready for use at the field level in 1995. Validation, testing, recoding, development of interfaces and parameterization are underway. Prior to 1995, considerable work is required by action agencies to prepare for implementation. These efforts include training, selection of equipment, development of input data sets, the development of guidelines and procedures for use of WEPP. These are major tasks and require considerable time and effort.

This chapter is not intended to be a general critique of the WEPP model, but rather an examination of model components where representing rangeland conditions or parameterizing and modeling the processes may be difficult. These components are related to hydrology, plant growth, erosion, and soil.

DESCRIPTION OF WEPP

The WEPP is a daily simulation model that computes the conditions of the soil and plant system that are important in runoff and soil erosion. If rainfall occurs, WEPP computes surface runoff. If surface runoff occurs, WEPP computes the soil that is detached and deposited down a hillslope and the amount delivered to a channel at the foot of a slope. These are all computed in the hillslope version of WEPP. Two additional versions (watershed or grid) are used to compute the erosion, deposition, and delivery of sediment through the channel system on the field or farm.

The WEPP represents the area where sheet and rill erosion occurs as a series of overland flow elements (OFE) beginning at the top of the slope and ending at a field boundary or a channel at the bottom of a slope. Each OFE is homogeneous with regard to the ecosystem, soil, and management.

Within an OFE, sediment detachment and transport occurs on rill and interrill areas. On interrill areas, the detachment is caused by raindrop impact, and transport is in very shallow flows that are impacted by raindrops. The detached and transported soil on an interrill area is delivered to a rill. Sediment detachment in a rill is caused by the hydraulic shear of the flow carried by the rill and is not affected by raindrops on the water surface. Sediment transport in a rill is also not affected by rainfall. Sediment deposition may occur in a rill if sediment load exceeds the transport capacity of the flow.

Plant Growth

The status of plants and plant residue when an erosion event occurs is vital to accurate estimation of soil detachment and transport. The status of below and aboveground biomass must be accurately estimated to evaluate the effect of various management alternatives on soil erosion. The WEPP calculates on a daily basis plant growth and the decomposition and accumulation of residue and litter.

Important plant growth characteristics include canopy cover and height, mass of live and dead below and aboveground biomass, leaf area index and basal area, residue, and litter cover. Information about management are input to the model. Many annual and perennial crops, management systems and operations that may occur on cropland, rangeland, forestland, pastures, vineyards, and gardens have been parameterized. Major efforts are underway to develop an expert system for selection of parameters to use in WEPP (Deer-Ascough et al., 1993). While this work is presently for cropland parameters, it is expected that parameters for rangelands will eventually be included.

Representation of the complex plant ecosystem on rangelands have proven difficult. On croplands, there is generally only one crop grown at a time. Rangelands are a complex system where numerous species coexist simultaneously, each using different amounts of water each day, and each having different above and below ground biomass accumulation rates. Additionally, they withdraw water from different soil depths. A question not yet fully answered is can we represent this complex system with a dominant plant, a few plant species, or a representative plant community? This question must be answered and necessary parameterization accomplished if we are to have an erosion prediction system on rangelands fully capable of representing existing and potential ecosystems and the varied management schemes practiced and proposed.

Decomposition is important in estimating residue and litter cover and soil erosion on rangelands and croplands. Coefficients for use in estimating litter and residue decomposition have been determined for many crops, but there has been little work on estimation of decomposition rates of surface litter found on rangelands. Furthermore, the location of litter is also highly variable. There may be in some ecosystems an accumulation of litter under shrubs, but this may not be the case for other litter that is more accessible and vulnerable to animal traffic. Both of these are areas of research needed to apply WEPP to rangelands.

Hydrology

The hydrologic cycle must be well represented if erosion and sediment delivery are to be accurately predicted. The WEPP uses several climate variables, including storm rainfall amount and duration, ratio of peak rainfall intensity to average rainfall intensity, time to peak intensity, daily maximum and minimum temperature, daily miles of wind by station and its direction, and solar radiation. These variables are required in components related to plant growth and surface litter decomposition, water balance, and in estimating runoff volume, duration, and peak rate.

The hydrologic component of the WEPP hillslope profile model is derived from the research Infiltration and Runoff Simulator (IRS) model (Stone et al., 1992). The IRS model is an event-based model that uses the Green-Ampt Mein-Larson (GAML) infiltration equation as modified by Chu (1978), and the kinematic wave equations as presented by Lane et al. (1988).

Several modifications have been incorporated into the IRS model to address the implementation constraints of simplicity and speed of execution. Rainfall disaggregation (Nicks & Lane, 1989) of daily precipitation was added to reduce the amount of data needed to describe rainfall intensity needed by both the GAML model and the interrill erosion model. An approximate method for computing the peak discharge at the bottom of a hillslope profile (Hernandez et al., 1989) was added to reduce model run time. Parameters for the hydrologic component can be identified through calibration, if observed data are available or estimated by the model from measurable physical properties of the soil and vegetation (Rawls et al., 1983; Weltz et al., 1992). In continuous simulation mode, baseline hydrologic parameters are adjusted in response to changes in canopy cover and litter caused by vegetation growth and decomposition, herbicide application, burning, and grazing by animals.

Preliminary testing of the WEPP model on rangelands has been started using data from the semiarid rangeland Walnut Gulch Experimental Watershed. Tiscareno et al. (1992) found that the hydrologic response of the hillslope model is most sensitive to rainfall amount, duration, and GAML baseline saturated hydraulic conductivity. For a given runoff producing rainfall event, the response is most sensitive to GAML baseline saturated hydraulic conductivity, soil moisture, and aboveground biomass. The parameter estimation techniques within the model and the procedure used to disaggregate rainfall events have been identified (van der Zweep et al., 1991) as critical components of the model requiring additional research. Improvements in estimation of the GAML baseline saturated hydraulic conductivity parameter and in adjusting its baseline value to account for the influence of changes in canopy cover and surface litter may greatly improve model accuracy.

Erosion

The WEPP models erosion on a rangeland hillslope by dividing the soil surface into two regions: rill (concentrated flow paths) and interrill. Rills are flow paths that form as water flow concentrates. Detachment in these channels is largely a function of flow shear stress (force exerted by water flow on the bed and banks). In many landscapes, these flow paths form at fairly regular intervals.

The area between rill channels is called the interrill area. Water flow on interrill areas is shallow, and most of the soil detachment here is due to raindrops impacting the soil surface. The raindrops also act to enhance the transport of previously detached sediment from the interrill area to the rill channels. Rills are the major sediment transport pathway for all sediment detached—both that from the rills and that supplied to the rills from the interrill areas.

The basic equation used in the WEPP erosion component is a steady state sediment continuity equation:

$$\mathrm{d}G/\mathrm{d}x = D_i + D_r \qquad [1]$$

where G is sediment load in the flow down a hillslope (kg s^{-1} m^{-1}), x is distance downslope (m), D_i is the interrill sediment delivery rate to the rills (kg s^{-1} m^{-2}) and D_r is the rill detachment or deposition rate (kg s^{-1} m^{-2}) (Nearing et al., 1989; Foster et al., 1989). For erosion computations for each individual storm, the time period used is the effective duration of runoff computed in the hydrology component of the model. Estimates of $\mathrm{d}G/\mathrm{d}x$ are made at a minimum of 100 points down a profile, and a running total of the sum of all detachment and deposition at each point from each storm is used to obtain monthly, annual, and average annual values for the simulation.

The interrill component of WEPP is currently a fairly simple sediment delivery function:

$$D_i = K_i I_e^2 G_e C_e S_f \quad [2]$$

where D_i is delivery of detached sediment to the rill (kg m^{-2}, K_i is the interrill erodibility (kg s^{-1} m^{-4}), I_e is the effective rainfall intensity (ms^{-1}) occurring during the period of rainfall excess, G_e is a canopy cover effect adjustment factor, C_e is a canopy cover effect adjustment factor, and S_f is a slope adjustment factor. The I_e is computed through a procedure that examines the time period over which rainfall excess is occurring. The effective duration of rainfall excess is passed to the erosion component from the hydrology component. Equation [2] lumps together the processes of detachment, transport, and deposition on the interrill areas.

The C_e is a function of the fraction of the soil surface area covered by canopy and the height of the canopy. The G_e is a function of the fraction of the interrill area covered by surface litter, residue, and rocks. The S_f is a function of the interrill slope:

$$S_f = 1.05 - 0.85\, e^{(-4 \sin B)} \quad [3]$$

where B is the interrill slope angle. These functions are based on reasonable fits to data reported by Meyer (1981), Meyer and Harmon (1984, 1989), and Watson and Laflen (1986).

An improvement to the WEPP erosion component might be the modeling of detachment, sediment transport, and sediment deposition as separate processes on the interrill regions to arrive at a better value for D_i. Since interrill processes may be more dominant than rill processes on consolidated rangeland soils, this improvement to the interrill component might improve erosion estimates for rangeland situations.

Concentrated flow paths are the major pathway for sediment movement down most hillslopes. Water flowing in such rills has the ability to both transport sediment and detach additional soil. When the rill flow becomes laden with sediment from either sediment supplied from the interrill areas or from sediment detached in the rill channel itself, the rill flow loses some of its ability to detach soil and transport sediment. If too much sediment is supplied and the flow system is overloaded, then no rill detachment can take place, and sediment deposition occurs. One of the strengths of WEPP is its ability to estimate both rill detachment and deposition, allowing comprehensive evaluation of both on-site and off-site effects of erosion.

The WEPP uses separate equations to simulate rill detachment and deposition. Rill detachment is predicted to occur when the flow shear stress exerted on the soil exceeds a critical threshold value, and sediment transport capacity is greater than the sediment load:

$$D_f = K_r\,(\mathrm{TAU} - \mathrm{TAU}_c)\,(1 - G/T_c) \quad [4]$$

where D_r is the rill detachment rate (kg s^{-1} m^{-2}), K_r is the adjusted rill erodibility parameter (s m^{-1}), TAU is the flow shear stress (P_a), TAU_c is the critical flow shear stress (Pa), G is sediment load (Kg s^{-1} m^{-1}), and T_c is the flow sediment transport capacity (kg s^{-1} m^{-1}). One can see from this equation that as the flow fills with sediment (G approaches T_c) that the rill detachment rate will be predicted to decrease. Sediment transport capacity in the WEPP model is predicted using the equation:

$$T_c = k_t \, \mathrm{TAU}^{1.5} \qquad [5]$$

where k_t is a transport coefficient [$m^{0.5}$ s^2 ($kg^{0.5}$)] calibrated and obtained by applying the Yalin (1963) equation at the end of the slope profile (Finkner et al., 1989).

When the sediment load exceeds the sediment transport capacity, the equation used by WEPP to predict deposition is:

$$D_r = ((\mathrm{BETA} \times V_{eff})/q)\,(T_c - G) \qquad [6]$$

where D_r is the rill deposition rate (kg s^{-1} m^{-2}), BETA is a rainfall-induced turbulence factor (currently set to 0.5), V_{eff} is an effective particle fall velocity (m s^{-1}), and q is flow discharge per unit width (m^2 s^{-1}). An area of concern with the current deposition equation is the estimation of the V_{eff} term based upon the particle-size distribution. An evaluation of the procedure that uses the smallest size classes is underway to determine how well the method and the deposition equation perform. Other areas for future improvement in the prediction of deposition would be to: (i) compute the BETA coefficient as a function of rainfall intensity and flow depth, instead of assigning it a constant value; and, (ii) alter the sediment transport equation used so that it includes a rainfall-enhancement term.

Rill characteristics such as spacing, width, and shape are important in estimating soil erosion. For rangelands, rill spacing is estimated as the average spacing of vegetation but spacing is never <0.5 m or >5 m. Estimation of rill width is based on flow and topographic characteristics, while rill shape is always assumed to be rectangular. These assumptions are being evaluated and are subject to change as additional information becomes available. Sensitivity analyses to date have indicated that rill characteristics are not as significant as several other characteristics in determining erosion and sediment delivery from rangelands.

Soil

The soil component deals with temporal changes in soil properties important in the erosion process, and in estimation of surface runoff rates and volumes. These include random roughness, ridge height, saturated hydraulic conductivity, soil erodibilities, and bulk density. The effects of tillage, weathering, consolidation, and rainfall are considered in estimating the status of soil properties.

Baseline interrill and rill erodibility, and critical hydraulic shear for a freshly tilled condition, are adjusted to other conditions based on time since tillage for cropland soils. For rangeland soils, the baseline condition is that of a long-term undisturbed soil under rangeland conditions with surface residue removed. For both range and cropland soils, adjustments to interrill erodibility are based on live and dead roots in the upper 150 mm of the soil and to rill erodibility because of incorporated residue in the upper 150 mm of the soil.

Past efforts to model erosion processes have used USLE relationships for estimating soil erodibility. A major WEPP effort has been extensive field studies (Elliot et al., 1989; Simanton et al., 1987) to develop the technology to predict erodibility values for cropland and rangeland soils from soil properties. A major effort continues for both rangelands and croplands to expand the data bases that support WEPP.

EROSION PREDICTIONS

The use of WEPP to evaluate different management is illustrated by applying the watershed version of WEPP to two common rangeland management scenarios; cattle grazing when the vegetation is brush, and cattle grazing the same area when it is in grass, perhaps after brush is controlled by herbicide application and the grass is established. The watershed is a hillslope on the Lucky Hills 103 watershed near Tombstone, AZ (van der Zweep et al., 1991), and data from these simulations are presented in Tables 2–1 and 2–2. The WEPP hillslope version

Table 2–1. Information on the management practices simulated using WEPP on the Lucky Hills 103 watershed, Walnut Gulch Experimental Watershed.

Vegetation	Management practice	AMU†	Utilization‡	Herbicide	Seeding
		(ha cow')	%		
Brush	No grazing	0	0	none	none
Brush	Moderate grazing	18	18	none	none
Grass	No grazing	0	0	once	once
Grass	Moderate grazing	12	20	once	once
Grass	Heavy grazing	2	85	every 4 yr	every 4 yr

†AUM is animal unit month.
‡Utilization is percentage of total standing biomass consumed by grazing livestock.

Table 2–2. Average annual watershed runoff volume, 2-yr return period watershed peak discharge, and hillslope and watershed sediment yield for five management practices for Lucky Hills 103 watershed, Walnut Gulch Experimental Watershed.

Vegetation	Management practice	Watershed runoff volume mm	2 yr watershed peak discharge mm h^{-1}	Sediment Yield	
				Hillslope	Watershed
Brush	No grazing	20	27	0.92	2.27
Brush	Moderate grazing	27	33	1.54	2.84
Grass	No grazing	15	24	0.08	1.70
Grass	Moderate grazing	17	26	0.10	1.74
Grass	Heavy grazing	18	38	0.16	2.13

93.0 was also applied to grazing intensity effects on soil erosion, runoff, and sediment concentration for the Edwards Plateau in Texas (Fig. 2–1, 2–2, and 2–3).

The examples shown are for WEPP simulations, the WEPP models are under development and are not completely verified, validated, and parameterized. When WEPP is fully verified, validated, and parameterized, exact quantitative results will probably be somewhat different. We do expect the present WEPP model with our present parameterization to represent trends that would occur in nature.

Table 2–1 lists the characteristics of the management practices for the Lucky Hills watershed near Tombstone, AZ. The two brush scenarios consist of no grazing or moderate grazing with no herbicide application or reseeding of grass. The three grass scenarios consist of an initial herbicide treatment to remove the brush, reseeding with grass, and three grazing intensities. The heavy grazing management practice necessitates reapplication of the herbicide and reseeding every 5 yrs.

The climate (precipitation, temperature,and solar radiation) used for the simulation of each management practice was a 15-yr sequence generated by the CLIGEN model (Nicks & Lane, 1989). Initialization of infiltration parameters was taken from van der Zweep et al. (1991). Soil erodibility parameters were taken from Laflen et al. (1991).

As grazing intensity increased, water and sediment yields also were predicted to increase, while conversion from brush to grass was predicted to have the opposite effect (Table 2–2). Increases in vegetation density and amount of residue on the soil surface because of brush to grass conversion or because of a lower grazing intensity increases infiltration, decreases runoff, and protects the soil surface from detachment by raindrop impact. The most significant impact was on hillslope sediment yield where conversion from brush to grass with no grazing was predicted to decrease hillslope sediment yield 91%.

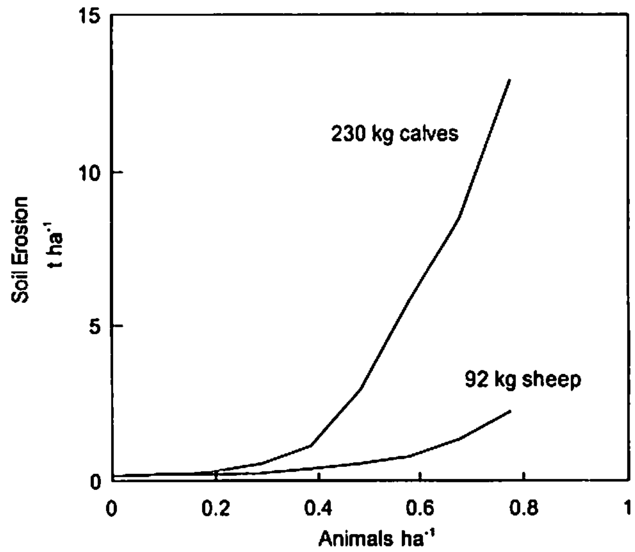

Fig. 2–1. Effect of grazing intensity on annual soil erosion for the Edwards Plateau region of Texas.

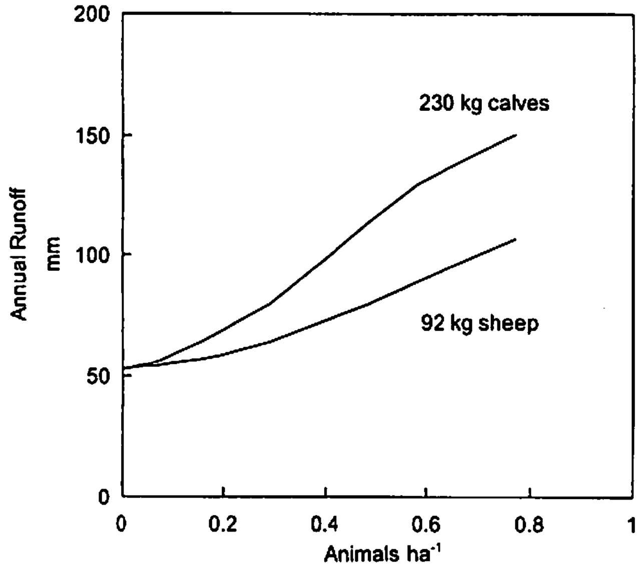

Fig. 2–2. Effect of grazing intensity on surface runoff for the Edwards Plateau region of Texas.

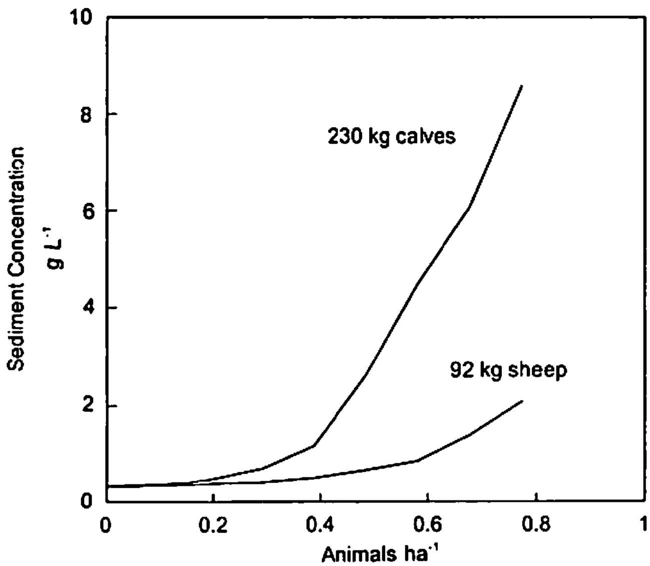

Fig. 2–3. Effect of grazing intensity on sediment concentration for the Edwards Plateau region of Texas.

The example shown in Fig. 2–1, 2–2, and 2–3 is for the Edwards Plateau region of Texas. As indicated earlier, information presented in Fig. 2–1, 2–2, and 2–3 are based on simulations using the WEPP model that is still under development. As development continues, predicted quantities and relationships will probably change because of model improvements, improved data, and improved parameter estimation. The information presented here is to demonstrate the power of the WEPP model, and to demonstrate potential use, not give exact quantitative results.

In this example, the WEPP hillslope version was run for a 20-yr weather period. The climate was again generated using CLIGEN (Nicke & Lane, 1989). Average annual generated rainfall was 625 mm. For this simulation, 92 kg sheep (*Ovis aries*) were contrasted with 230 kg stocker calves (*Bos taurus*) to demonstrate the sensitivity of the rangeland component to different stocking rates of livestock. Grazing periods simulated were from about 15 March to 31 October of each of the years of simulation. Some grazing rates were probably in excess of feasible rates.

As shown in Fig. 2–1, WEPP demonstrated a sensitivity to grazing intensity. Soil erosion predicted in this case was sediment delivered from a 100 m long 9% slope. Soil erosion rates were quite high when stocking rates were high for the 230 kg calves, but until stocking rates exceeded 0.30 animals per ha for the 7.5-mo grazing period for this size animal, there was little impact of stocking rates on soil erosion rates. The model demonstrated as forage consumption increases, the risk of soil erosion increases once a critical threshold of canopy and ground cover has been passed. The WEPP model estimates daily biomass growth and daily biomass use and loss. This information is then used to estimate canopy and litter cover. For a given climate, the WEPP model would predict that increased stocking rates would increase daily forage consumption, which would decrease canopy cover and increase soil erosion and runoff. The daily forage consumption per animal is based on the work by Brody (1945) as expressed in Eq. [7].

$$F = 0.1(B_w^{0.75}/D) \qquad [7]$$

where F is daily forage consumed (kg) per animal, B_w is the body weight of the animal (kg), and D is digestibility (a fraction between 0 and 1) of the forage.

Similarly, as shown in Fig. 2–2, simulated average annual runoff would be predicted to increase as grazing intensity increased, but not as dramatically as did soil erosion. For this simulation, intensive grazing was predicted to reduce ground cover, both litter and canopy, which was predicted to increase surface runoff and to increase soil erosion.

Estimated average annual sediment concentrations, based on estimated soil erosion and runoff amounts, were low until stocking rates increased above a threshold level (Fig. 2–3). Sediment concentration is an important parameter to those interested in offsite effects of management, but it is not a parameter that can be computed using Universal Soil Loss Equation prediction technology. This illustrates one of the new uses for which the WEPP technology can be applied, on both rangeland and cropland. Additional available information includes enrichment ratios based on specific surface area of eroded sediment delivered from hillslopes, and for sediment delivered from small watersheds.

Research on the influence of grazing by livestock on erosion has demonstrated that light grazing can not be detected from no grazing (Thurow et al., 1986; McGinty et al., 1979; Blackburn et al., 1982). In many cases research has demonstrated that moderate grazing is similar to no grazing in respect to soil erosion and runoff volume (Weltz & Wood, 1986a, b; Johnson et al., 1980; Wood et al., 1986). The WEPP model reflects this fact by not indicating an acceleration in soil erosion until the stocking rate of 30 230-kg animals per square kilometer (0.3 animals ha^{-1}) has been reached. If we use the soil tolerance concept of 2 t ha^{-1} as excessive erosion then the maximum stocking rate would be between 40 and 50 230 kg animal km^{-2} or nearly 80 to 92 kg animals km^{-2}. This example demonstrates how the WEPP model may be able to assist ranchers and conservationists in setting stocking rates that avoid accelerated erosion on western rangelands.

SUMMARY AND CONCLUSIONS

The WEPP model for soil erosion prediction is being developed to work for all land situations in the USA. Its major limitations on rangelands are accurate representation and parameterization of rangeland soils, surfaces, and ecosystems. Major efforts are underway to overcome these limitations.

As shown here, WEPP can be used to evaluate alternative rangeland management for specific sites. In the past, it has been difficult to easily evaluate the effectiveness of a specific practice across a wide range of conditions. The WEPP's ability to simulate the wide range of climates, topographies, ecosystems, and soils should make such evaluations routine when WEPP is completely parameterized and validated.

The WEPP brings to the managers' tool kit a new tool that provides new information of importance not only for protection of the grazing resources, but for evaluation of offsite impacts of rangeland management and conservation practices. As the demands of the twenty-first century increase our reliance on a dwindling natural resource base, WEPP and other natural resource models will assume greater roles in management of these resources.

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