

MODELING EROSION UNDER FUTURE CLIMATES WITH THE WEPP MODEL

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Abstract The Water Erosion Prediction Project Climate Assessment Tool (WEPPCAT) was developed to be an easy-to-use, web-based erosion model that allows users to adjust climate inputs for user-specified climate scenarios. WEPPCAT allows the user to modify monthly mean climate parameters, including maximum and minimum temperatures, number of wet days, precipitation, and precipitation intensity (change in heavy precipitation events) in order to assess changes in surface runoff and soil erosion. In addition, the model allows the user to assess the impacts of a variety of land management alternatives including riparian filter strips. An important aspect of the tool is that databases for the model are pre-constructed; therefore, it does not require specialized scientific expertise to run, and scenarios are quick and easy to set up. This paper presents the conceptual and technical basis for WEPPCAT, and an example application is given for sediment delivery on a transect running north-south from Minnesota to Louisiana under several climate change scenarios.

INTRODUCTION

Changing climate will influence soil and water resources throughout the world. There have been many studies that predict future climates and how they could affect soil and water resources (e.g., IPCC, 2007). Precipitation over the contiguous United States has changed throughout the last century. Groisman et al. (2001) found that average annual precipitation has increased 6 percent over the period from 1910 to 1999. They found that this increase in precipitation was not equally weighted throughout the seasons. Winter was found to have no change while rainfall in the spring increased 10 percent, the summer increased 7 percent and the fall increased 15 percent. Kunkel et al. (1999) found that precipitation increased at a rate of 1.3 percent per decade over the period from 1931 to 1996.

The past century's increase in total precipitation seems small when compared with the changes some scientists are predicting we may see over the next century. The IPCC reports a projected mean precipitation increase of 20 percent across the northern United States (Christensen et al., 2007), with more than 30 percent in some regions. Increase in total precipitation has not been the only change in precipitation that has occurred during the last century. Historical climate data has shown that there has been a worldwide increase in the portion of precipitation falling in heavy and very heavy rainfall events. In an analysis of precipitation trends throughout the United States between 1910-1999, Groisman et al. (2001) reported an increase of 1.7 percent per decade for heavy precipitation events (95th percentile), 2.5 percent increase in very heavy (99th percentile), and 3.3 percent increase per decade in extreme precipitation events (99.9th percentile).

percentile). Pruski and Nearing (2002) found that change in precipitation intensity would cause a greater change in runoff than change in precipitation due to the number of wet days (i.e., days with precipitation). More runoff will lead to increased soil erosion and sediment delivery.

Erosivity is the ability of rainfall to detach and transport soil and is a function of both storm energy and peak intensity (Wischmeier and Smith, 1978). Nearing (2001) applied two coupled Atmosphere-Ocean Global Circulation Models to estimate the effect of precipitation changes on rainfall erosivity in the 21st century. Erosivity was modeled using results from the global climate models from the Hadley Centre (HadCM3) and the Canadian Centre for Climate Modeling and Analysis (CGCM1 HG+A1). The climate data from each of these models was run for 40-year and 80-year time periods. The most conservative results from the study indicated an average of 17 percent change (either positive or negative) in the magnitude of erosivity from current climate conditions; with the most dramatic results predicting a 58 percent increase in erosivity. The results also highlighted the fact that changes will likely be spatially varied, with some regions seeing an increase in rainfall-erosivity and others seeing a decrease. Nearing et al. (2004) reported that when rainfall increases, runoff and erosion increase at an even greater rate. For example, a 1 percent increase in annual precipitation can increase erosion by 1.7 percent, if other factors are equal.

As we look forward to the next era in soil and water management, one of the greatest challenges we face are the unknowns associated with climate change. It is now widely accepted that stationarity, “the idea that natural systems fluctuate within an unchanging envelope of variability”, is no longer an acceptable assumption to guide our water-resources risk assessment and planning (Milly et al., 2008). Climate change could increase soil loss rates and associated water quality impairment. Responding to this challenge requires the development of soil and water management strategies that are robust to potential future changes in climate.

The objective of this paper is to develop a method to assess the impacts of climate change and management practices on soil erosion. More specifically, we (1) developed the Water Erosion Predication Project Climate Assessment Tool (WEPPCAT), a web-based interface to the Water Erosion Predication Project (WEPP) model to assess the impacts of climate changes on soil erosion and management practices (e.g., riparian filter strips) and (2) applied the WEPPCAT to five locations along the north-south transect from Minnesota to Louisiana.

METHODS

WEPP Model The WEPP model is process-based and includes modules for infiltration, runoff, daily water balance, storm disaggregation, soil erodibility changes, plant growth, and residue accumulation and decomposition (Nearing et al., 1989, Flanagan and Nearing, 1995; Laflen et al., 1997). The WEPP hillslope version simulates the detachment, transport and deposition of sediment on a single hill side. In WEPP, rill detachment occurs when two conditions are met: when hydraulic shear stress of the runoff exceeds the critical shear stress of the soil and when sediment load in a rill is less than sediment transport capacity of the rill flow. Interrill erosion depends on interrill soil erodibility, rainfall and runoff intensity, canopy cover, slope steepness and litter or ground cover. Rill erosion and/or deposition depend on the ratio of sediment load to transport capacity, rill erodibility, hydraulic shear stress, surface cover, sub-surface residue, and

soil consolidation. The WEPP model has four input files: daily weather, vegetation or management, topography, and soil. Databases for soils and vegetation for a wide range of agriculture, rangeland and forest conditions have been developed.

The WEPP model is a daily simulation model that adjusts the hydrologic status of the land for each day that the simulation is run. The daily weather inputs include the amount of precipitation and duration, the ratio of peak intensity to average intensity, the time at which peak intensity occurs, solar radiation, maximum and minimum temperature, dew point temperature, and wind velocity and direction. Daily weather data for input to the WEPP model are usually generated using the CLIGEN weather generator (Nicks et al., 1995) and long term weather statistics from more than 2500 stations in the U.S. or the PRISM precipitation database (Elliot, 2004). The CLIGEN model generates daily weather for any desired number of years of statistically representative weather data based on statistics from National Weather Service records. There are 14 statistical parameters that represent the climate used by CLIGEN: mean, standard deviation and skew of monthly precipitation on a wet day; the probabilities of a wet day following a dry day and of a wet day following a wet day; the mean and standard deviation of monthly maximum and minimum temperatures and solar radiation; the mean monthly maximum half hour rainfall depth; the monthly mean dew point, the statistical distribution of rainfall intensity, and the means and standard deviations of wind velocity and direction (Flanagan and Nearing, 1995).

WEPP has been shown to be an effective tool for modeling erosion rates for a wide range of climatic and other conditions, making it well suited to addressing the impacts of a changing climate on soil erosion. WEPP has been subjected to many tests comparing it to observed data and the Universal Soil Loss Equation (USLE); and has in most cases performed satisfactorily. (Laflen et al., 1997; Flanagan and Nearing, 1995; Nearing et al., 1989).

WEPPCAT WEPPCAT is an interface for the WEPP model introduced in 2008. WEPPCAT uses the same input files as WEPP, and so can utilize extensive climate, soil, plant, tillage, management and topographic databases for the United States and elsewhere. The interface is web-based and the current URL is www.WEPPCAT.net. The interface includes drop down menus for a number of typical soils and vegetation or management files. WEPPCAT has been integrated with an enhanced version of the Rock:Clime model (Elliot, 2004) that is a US Forest Service climate generator tool to simplify modifying part of the CLIGEN input files. This feature allows users to produce alternative climate scenarios for input to the WEPP model. The Rock:Clime interface allows WEPPCAT users to adjust climate with four monthly mean parameters; (1) maximum temperature, (2) minimum temperature, (3) precipitation amount, (4) number of wet days, and (5) (a unique WEPPCAT feature) the intensification of heavy precipitation events (greater than 95th percentile). These parameter values for climates can be obtained by downscaling from future global climate models (Zhang 2007) or downloaded from a Forest Service Rocky Mountain Research Station (RMRS) web site (Crookston, 2009). The user is responsible for choosing the future climate model and scenario.

Adjusting Precipitation Patterns of precipitation can change in a variety of ways. In the most basic sense, change in total precipitation amounts (e.g., monthly or annual averages) can be achieved by changing the number of days with precipitation (wet days) in a given month or year, by changing the amount of precipitation on a wet day, or both. Pruski and Nearing (2002)

suggested that in order to adjust precipitation for future climate change, half of any change in total rainfall should be accounted for by a change in number of wet days and half by a change in the daily precipitation amount. Rock:Clime allows the user to make such adjustments by altering the number of wet days per month and monthly precipitation amount. In addition, WEPPCAT has modified the Rock:Clime interface to allow the user to further increase the percentage of heavy precipitation events (greater than 95th percentile) up to 25 percent.

Observed 20th century trends in rainfall patterns in the United States suggest that historical spatial relationships between rainfall and rainfall erosivity are not stationary (Groisman et al., 2001). WEPPCAT is the first erosion prediction tool to allow users to account for this non-stationarity of rainfall distributions. The WEPPCAT rainfall intensification tool provides the capability for users to create climate change scenarios reflecting changes in the proportion of heavy (95th percentile), very heavy (99th percentile) and extreme (99.9th percentile) precipitation events, e.g. those found by Groisman et al. (2001) to be increasing. When rainfall is intensified the portion of very heavy and extreme precipitation events is increased more than the portion of heavy events.

In WEPPCAT the term "intensification" refers to an increase the total depth of precipitation falling in a given day (mm/day). Precipitation intensity in WEPPCAT is analogous to the terms 'storm magnitude' and 'heavy precipitation (greater than 95th percentile)' as used by Groisman et al. (2001). WEPPCAT does not refer to precipitation intensification specifically as a rate of rainfall (mm/hr), as is commonly assumed. The within-storm precipitation intensity is determined as a function of the total precipitation amount with a peak intensity defined statistically by CLIGEN (Arnold and Williams, 1989) and the storm hyetograph determined by the WEPP disaggregation routines (Flanagan and Nearing, 1995). It is also important to understand that WEPPCAT does not attempt to model changes in wet and drought period sequences, which are also anticipated to change under a non-stationary climate (IPCC, 2007), although Arnold and Elliot (1996) noted that wet spell and dry spell lengths predicted by CLIGEN were not different from observed spell lengths.

Precipitation "intensification" is calculated using the following empirically derived formula:

$$P_n = sd_n \times (1 + x \times 0.776) \quad (1)$$

where P_n = precipitation (mm/day) at a given standard deviation; sd_n = the relevant standard deviation; and x = the percentage change in intensification selected by the user. Average soil erosion rates are determined by the largest precipitation events within the period of interest. Thus, when predicting soil erosion risk, the number and intensity of large storms are going to be the dominant influence on erosion during any given period. The distribution of these large storms can be described by storms less than the 95th percentile, and greater than the 95th, 99th, and 99.9th percentiles of daily precipitation amount.

We studied the distribution of daily precipitation amounts generated by the CLIGEN model for a typical historic weather record and for scenarios with increasing intensification. Figures 1-4 illustrate the distribution of events generated by the CLIGEN weather generator beneath the 95th, above the 95th, 99th and 99.9th percentile respectively, for a baseline condition (current climate

condition), 20% increase in intensification without total precipitation change, and 20% increase in total precipitation without change in intensification. The figures 2-4 show that when intensification is increased, the magnitudes of high (95th percentile), and very high (99th percentile) or extreme (99.9th percentile) precipitation events become larger and the maximum tail of the distributions shift to the right. In order to account for this change without increasing the total amount of precipitation, the frequency of lower magnitude events also increases on the lower side of the distribution, increasing the skewness of the distribution (figure 1).

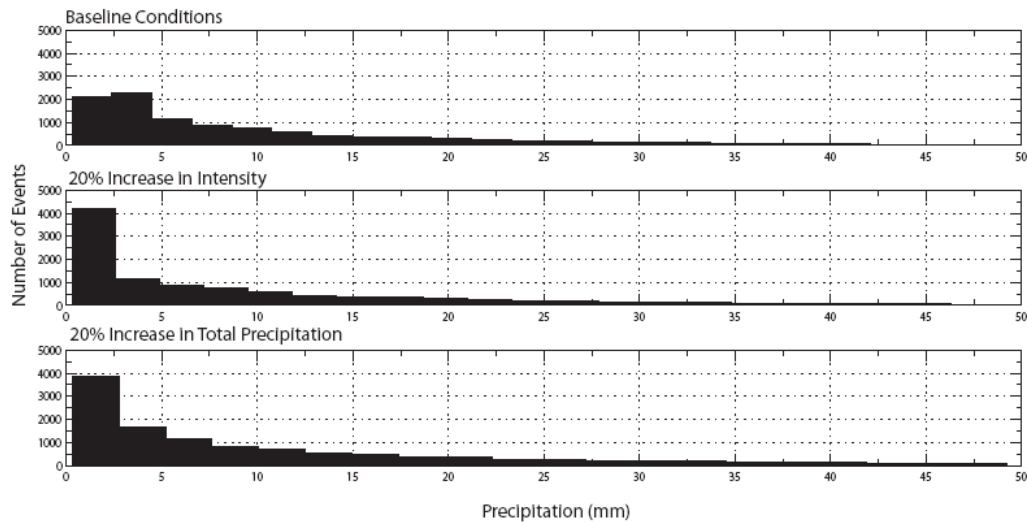


Figure 1 Frequency of precipitation events below the 95th percentile.

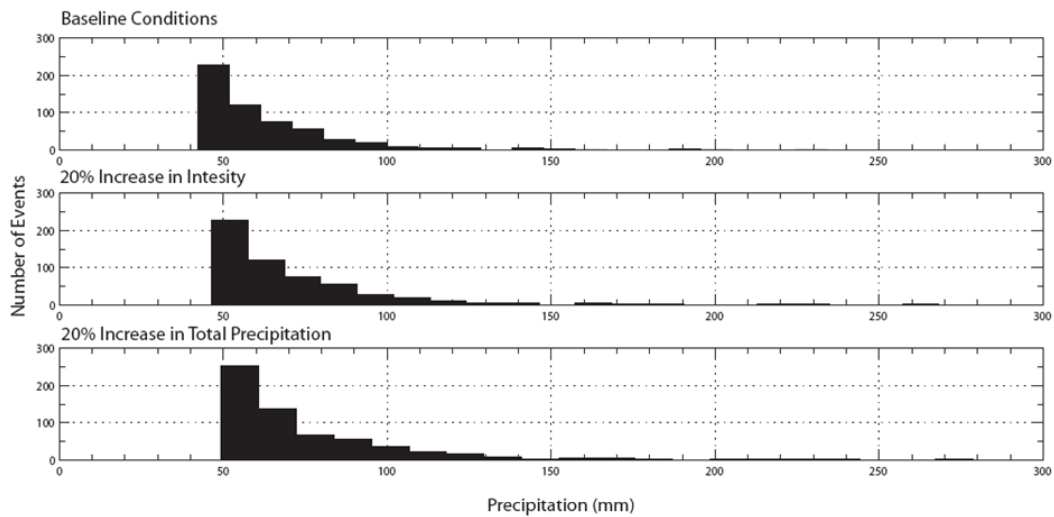


Figure 2 Frequency of precipitation events at the 95th percentile and above.

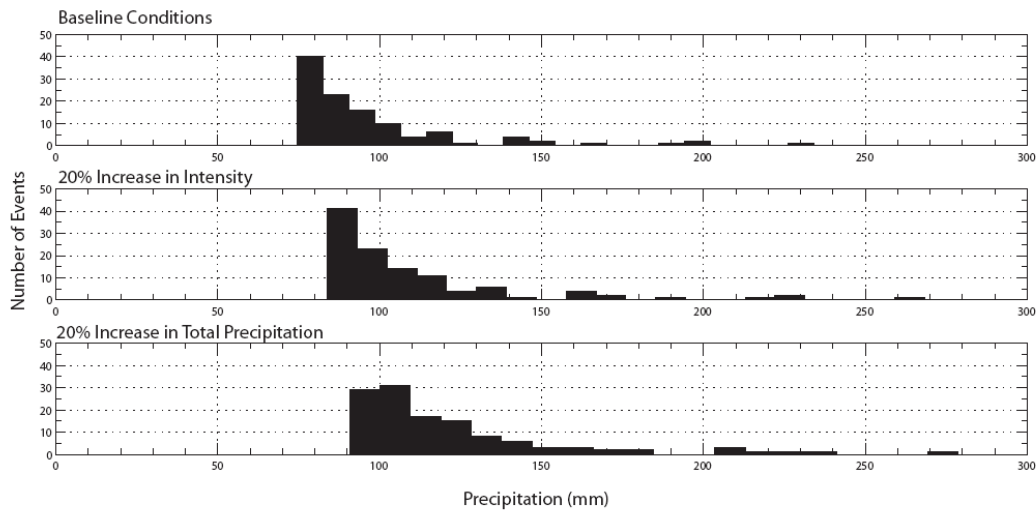


Figure 3 Frequency of precipitation events at or above the 99th percentile.

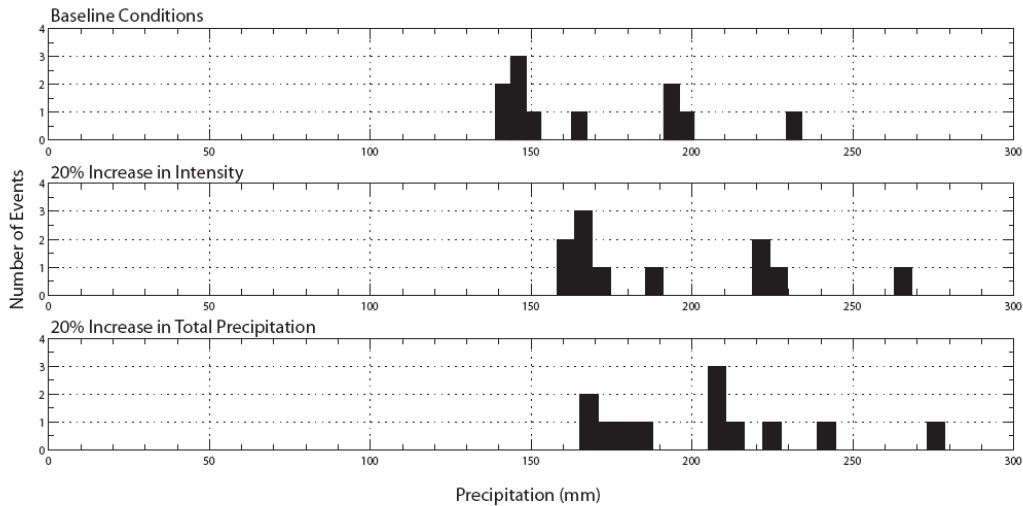


Figure 4 Frequency of precipitation events at or above the 99.9th percentile.

When total precipitation amount is changed, the number of wet days and/or the average daily precipitation amount must change. Pruski and Nearing (2002) recommended that both the number of wet days and the precipitation amount should increase with increasing precipitation. If we were to increase the total number of wet days without increasing the total precipitation, the precipitation amount per event would decrease in order to have the same total precipitation amount. It is important to understand the relationships among these precipitation parameters when adjusting them for climate change using the WEPPCAT or similar interfaces so that precipitation intensification is not unintentionally changed. The relationships among the precipitation parameters are displayed in table 1.

Table 1 Relationships among total precipitation, intensity, and number of wet days.

To have the same value of:	<u>Changing precipitation parameter</u>		
	Total precipitation	Intensification	Number of wet days
Total precipitation	N/A	+	-
	N/A	-	+
Intensification	+	N/A	+
	-	N/A	-
Number of wet days	+	+	N/A
	-	-	N/A

+ Increase in value. - Decrease in value.

Filter Strip Assessment WEPPCAT has a riparian filter strip assessment tool that can be used in conjunction with the climate change tool. If a climate change scenario modeled in WEPPCAT increases the sediment yield above the threshold level that is the tolerable sediment delivery amount given the current climate regime, the filter strip assessment tool can be used to identify the filter strip width which, if implemented, would keep sediment yield at its current rate under a given future climate scenario. The filter strip assessment tool provides the user an opportunity to evaluate the effectiveness of the riparian filter strip to limit sediment yield increases should they be predicted under changing climatic conditions.

Example Applications This section describes an example of the application of WEPPCAT to assess the impacts of climate changes on sediment delivery and the effectiveness a filter strip to offset climate impacts. Included are examples of how to use precipitation intensification and the filter strip assessment tools. WEPPCAT was run for five locations along the north-south transect from Minnesota to Louisiana at sites near Zumbrota, Minnesota; Marshaltown, Iowa; Carrolton, Missouri; Hot Springs, Arkansas; and Winnfield, Louisiana. Moving from north to south along this transect, annual precipitation increases and baseline sediment yield increases as well.

In all locations, a loam soil texture was used and the soil erodibility properties for each soil are presented in Table 2. The slope steepness was assumed to be 3 percent and field dimensions were assumed to be 30 m by 30 m for all sites. Field management for all scenarios was winter wheat, with conventional tillage. Three climate change scenarios were considered in this study: (1) increase in total precipitation, (2) increase in daily precipitation amount, and (3) increase in both total precipitation and daily amount (Table 3). When total precipitation was increased, daily precipitation and the number of wet days were each increased by half of the increase in total precipitation as suggested by Pruski and Nearing (2002). In each of these scenarios increases of 0, 5, 10, 15, 20 and 25 percent were modeled.

Each climate change scenario was also run with filter strips to illustrate how climate change affects filter strip widths to maintain current soil loss rates. In each case a 3-m bluegrass filter strip was used for the baseline run of the model. After the baseline was set, the model was run again for the three climate change scenarios (Table 3).

Table 2 Soil characteristics for WEPPCAT application locations.

Location	Minnesota	Iowa	Missouri	Arkansas	Louisiana
Soil	Ames	Armster	Armster	Alleghany	Barclay
Sand (%)	43.77	37.96	37.96	47.07	62.35
Clay (%)	28.3	30.47	30.47	22.63	13.2
Organic Matter (%)	0.723	0.723	0.723	1.203	2
Cation Exchange Capacity	23.53	25.27	25.27	12.83	7.9
Rock Fragments (%)	4.47	6.97	6.97	8.1	0.55
Interrill Erodibility $10^6 \times \text{Kg/s/m}^4$	5.31	5.13	5.13	5.31	5.31
Rill Erodibility $10^{-3} \times \text{s/m}$	8.5	8.5	8.5	6.4	6.2
Hydraulic Conductivity, mm/h	6.02	6.02	6.02	6.27	6.35

Table 3 Details of the three climate scenarios used for example, for the 25 percent increase in total precipitation or/and daily amount following recommendations of Pruski and Nearing (2002).

Climate change scenario	Percent increase in precipitation parameter		
	Total precipitation	Intensification	Number of wet days
1. Increase in total precipitation	25	0	12.5
2. Increase in intensification	0	25	0
3. Increase in total precipitation & intensification	25	25	12.5

RESULTS AND DISCUSSION

WEPPCAT projected that sediment yield would increase with increases in total precipitation and intensification (figures 5, 6, and 7). This trend is supported by the commonly accepted precipitation-erosion relationship; i.e., when precipitation increases, erosion increases (Lal and Elliot, 1994). The results also show that the sediment yield is higher in the south than in the north, since historic average precipitation is higher further south along the transect. The increase in total precipitation and erosion are greater in the wetter areas than the drier areas, because both total precipitation and intensification were increased as a percentage of the historic averages, therefore, leading to larger increase in sediment yield. When total precipitation alone is changed, the sediment yield increased more in the southern portion of the transect than in the north.

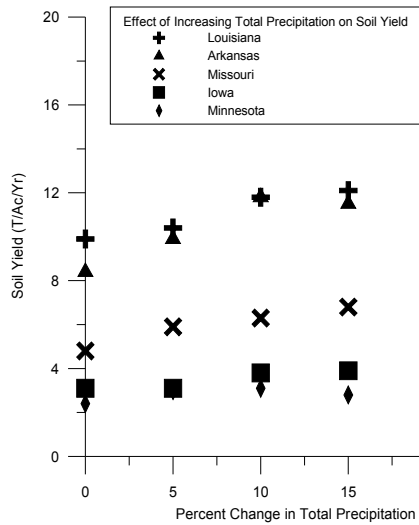


Figure 5 Effect of increase in total precipitation on predicted sediment delivery.

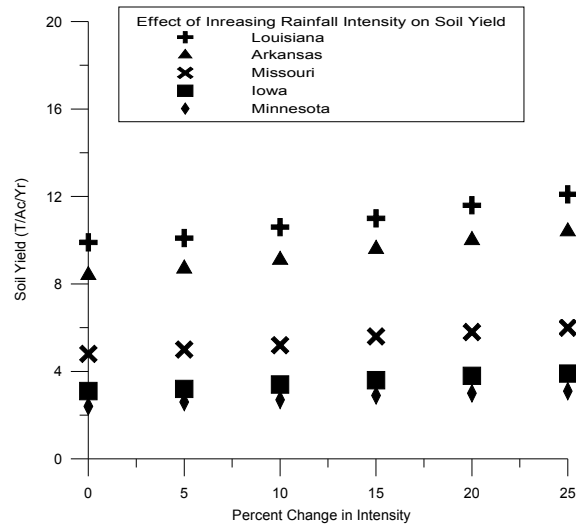


Figure 6 Effect of increase in intensification on predicted sediment delivery.

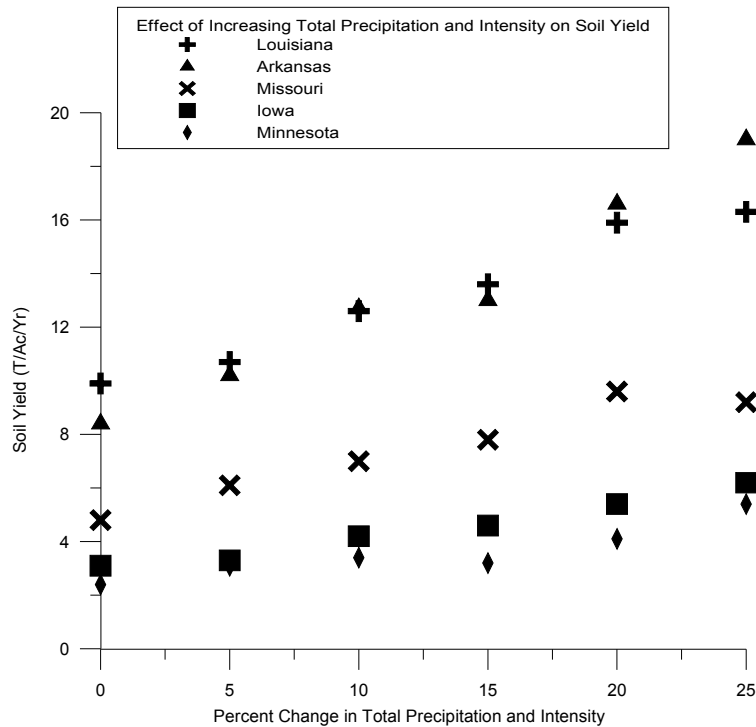


Figure 7 Effect of increase in total precipitation and intensification on predicted sediment delivery.

Both increased intensity and increased precipitation amount lead to increased sediment delivery. A comparison of Figures 5 and 6 shows that precipitation amount plays a greater role than intensification in increasing sediment delivery. Considering that increase in sediment delivery can be the result of change in precipitation intensification only, and not just a result of increase in

total precipitation, change in precipitation intensification is important for assessing sediment yield and management practices for future climates. Also, change in temperature distribution could affect seasonal runoff patterns in a region. For example, warmer climates in the Upper Midwest may lead to more rainfall events during the winter months rather than snow. Rainfall intensity is generally greater than snow melt rates, leading to an increase in erosion for the same total amount of winter precipitation. It is also possible that warmer summer temperatures could increase evapotranspiration, leading to drier soils and reduced runoff and erosion.

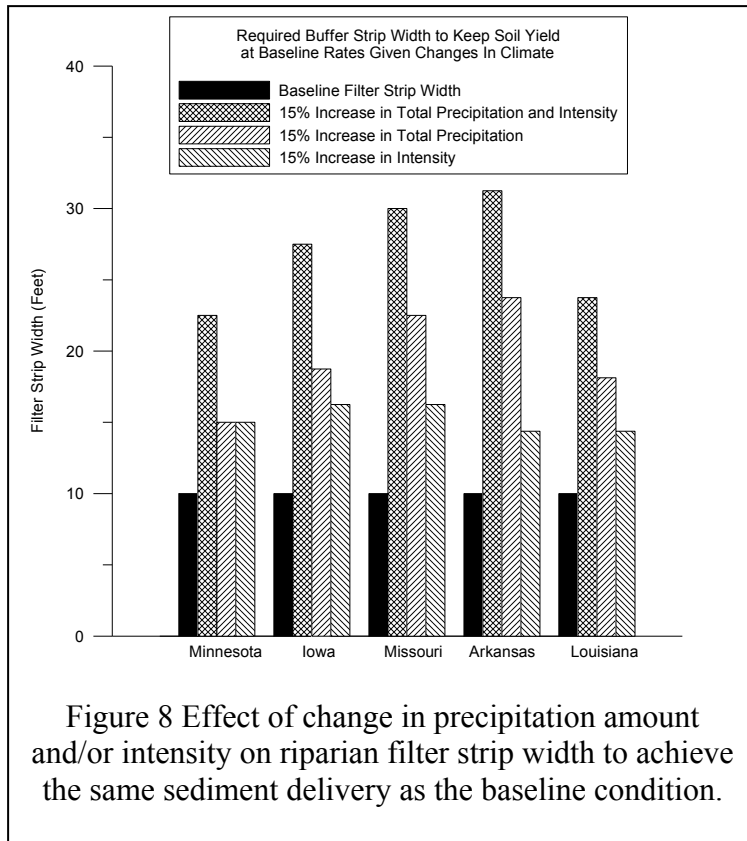
Even though the increase in precipitation is less in the northern states, the predicted sediment yields in the northern areas increased more as a percentage of baseline values (Table 4). When both total precipitation and intensity are increased, predicted sediment delivery increases, but their combined effect within the model is not as great as the product of their individual effects. (e.g., for Minnesota, $1.792 \times 1.292 = 2.315$, or an increase of 132 percent compared to 125 in Table 4).

Table 4 Percent increase in predicted sediment delivery.

Percent Change in Sediment yield	Minnesota	Iowa	Missouri	Arkansas	Louisiana
25% Increase in precipitation	79.2	61.3	52.1	88.1	36.4
25% Increase in intensity	29.2	25.8	25	23.8	22.2
Product combining increases in lines 1 and 2	132	103	90.1	133	66.7
25% increases in precipitation and intensity	125	100	91.7	126.2	64.6

Filter Strip Results. Figure 8 shows that both the amount of sediment delivered (Figures 6 and 7) and the climate determine the width of filter strip necessary to offset the additional sediment delivered by a more erosive climate. For example, Iowa had a 100 percent increase in sediment delivery compared to 125 percent for Minnesota, but required an 18 ft increase in strip width to offset this increase, compared to only 12 ft increase in filter strip for Minnesota. In some cases, the recommended buffer strip widths would not be practical. For example, increasing a buffer width from 3 m to 10 m on a 30-m long field would reduce the length of productive farmland by 7 m, a 24 percent loss of farmland to riparian buffer. In such case, other management practices may be preferable to keep the sediment delivery under future climate at the current level.

The findings point towards the importance of considering site-specific conditions, like climate, topography, and management practices, to ensure that sediment delivery from future climates is maintained at current levels. If the entire transect studied were to be subject to the same changes in total precipitation or in daily amount, the predicted sediment delivery rates for the northern portion of the transect have a greater percentage increase than further south. Regions that have historically low precipitation will have higher percentage increase in the rate of sediment



development of management strategies for reducing the risk of sediment delivery that will likely be associated with wetter climates in the future.

The tool showed that generally, if precipitation patterns are increased by the same percentages, southern U.S. areas should expect greater increase in sediment delivered across riparian filter strips than northern areas, likely due to higher precipitation amounts but the drier northern areas will experience a greater percentage increase in sediment delivery.

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delivery given the same percentage increase in total precipitation or intensity. Thus, drier areas, which may not be as familiar with soil conservation techniques, may need to be warned of the potential risks to their watersheds. Another finding is that a combined increase in intensity and total precipitation will lead greater soil loss than will either of the two factors on their own.

SUMMARY AND CONCLUSIONS

A new online tool, WEPPCAT, was developed to estimate soil erosion and filter strip effectiveness for future climates. The WEPPCAT interface is useful for understanding the sensitivity of soil loss to changes in climate, and to guide the

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