The site and condition specific nature of sensitivity analysis

V.A. Ferreira, G.A. Weesies, D.C. Yoder, G.R. Foster, and K.G. Renard

ABSTRACT: Sensitivity analyses generally aim to quantify model result changes with respect to input changes. This study instead focuses on the site- and condition-specific nature of sensitivity, to demonstrate why users benefit by conducting their own sensitivity analyses as an essential step in model applications. This is demonstrated by employing the RUSLE model, which predicts average annual soil loss within a field. Sensitivity of computed soil loss to changes in selected parameters and variables is quantified under a range of sites and conditions.

Input parameters representative of several common forms are varied about base values for the variety of scenarios. The scenarios include a corn/soybean rotation near Chicago, Illinois, the same scenario moved to the Atlanta, Georgia, area, and a corn/soybean/winter wheat rotation near Topeka, Kansas. Both conventional and no-till management schemes are tested at the three locations. Results show that model sensitivity may vary both with site and with management conditions being simulated. These results serve to caution users of complex computer models not to rely upon sensitivity results that were conducted under conditions other than those being simulated. A serendipitous result is the demonstration of how the form of presenting results affects user perspective of the importance of those results.

A sensitivity analysis is a methodical study of the response of selected output variables to variations in parameters and/or driving variables (Lane and Ferreira 1980). This provides valuable information and insight to modelers and model users. Model users refer to sensitivity analysis results to guide their parameterization efforts, using more resources to quantify those parameters to which the model is most sensitive. Sensitivity analysis also yields information that is essential for first-order uncertainty analysis.

In addition to the expected quantification of sensitivity, such analyses are useful to modelers in the verification step of project development. They serve to vigorously exercise the program, often exposing model and program errors. The difference distinguished here is between the *model*—equations, definitions, and other underlying relationships, and the *program*—computer code, which implements the model. For successful technology transfer efforts it is essential that the bulk of inevitable "bugs" be discovered and remedied before release of the *computer model* (the "package"—a model, implemented in a program, with associated databases).

V.A. Ferreira is a mathematician with the USDA–Agricultural Research Service, TERRA Laboratory, Ft. Collins, CO; G.A. Weesies is a conservation agronomist with the USDA–Natural Resources Conservation Service, National Soil Erosion Research Laboratory, W. Lafayette, IN; D.C. Yoder is an assistant professor, University of Tennessee, Knoxville; G.R. Foster is laboratory director, USDA–ARS, National Sedimentation Laboratory, Oxford, MS; and K.G. Renard is a retired research hydraulic engineer, USDA–ARS, Southwest Watershed Research Center, Tucson, AZ.

J. Soil and Water Cons. 50(5) 493-497

The Revised Universal Soil Loss Equation (RUSLE) computer model (Renard et al. 1991; Renard et al. 1994) is a popular method for estimating annual soil loss on agricultural areas under a wide variety of field, climatic, and management conditions. Land managers use RUSLE to guide the design of strategies that minimize soil loss. RUSLE is a complex implementation of the Universal Soil Loss Equation (Wischmeier 1976; Wischmeier and Smith 1978), which follows:

$$A = R\,K\,L\,S\,C\,P \tag{1}$$

where

A is computed average annual soil loss
R is a rainfall-runoff erosivity factor
K is a soil erodibility factor
LS is a topographic factor combining the slope length factor, L, and slope steepness factor, S
C is a cover-management factor and
P is a supporting practices factor.

While the equation itself is simple, accurately quantifying individual factors is not a trivial task, and requires professional knowledge or guidance. RUSLE provides such guidance, incorporating state-of-the-art, user-friendly submodels for determining values for each factor based upon input data describing field conditions, climate, and agricultural management. Included in RUSLE are databases that are generously populated (and easily modified, if needed) with information about agronomic crops, common field operations, and climate for many locations throughout the United States. Model and

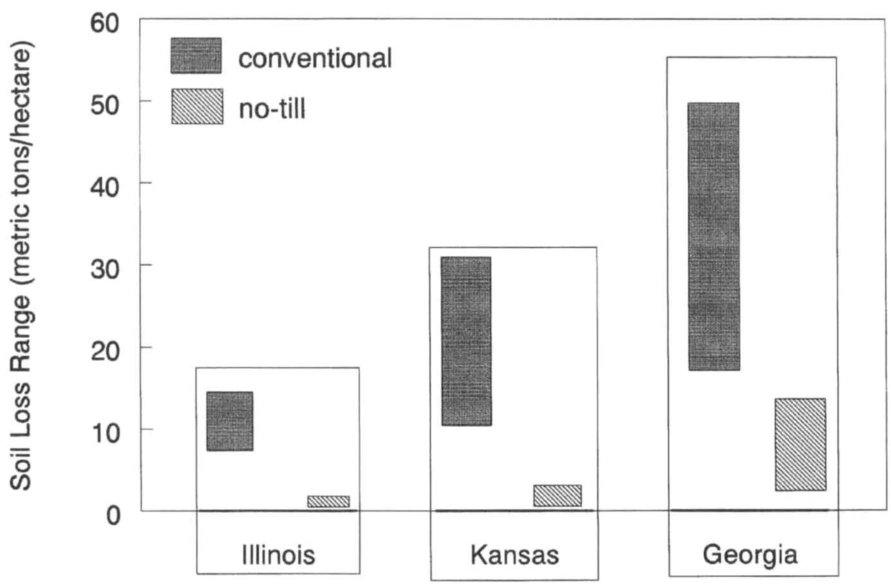

Figure 1. Ranges of conventional and no-till responses to location variations
Note: The top and bottom of each bar indicate the maximum and minimum soil loss values, respectively.

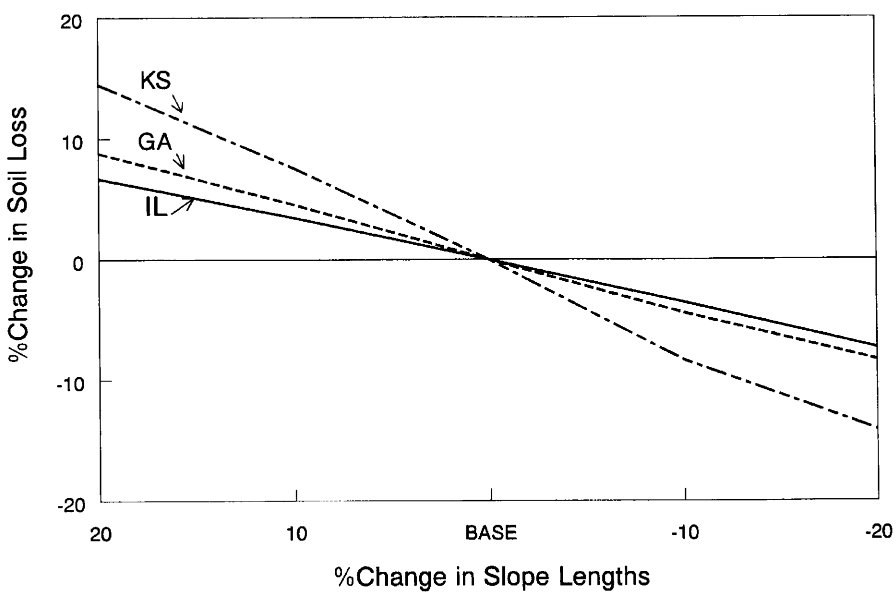

Figure 2. Responses to perturbations of ± 10% and 20% about the base Slope Lengths, in relative terms of percentage change in soil loss from base-predicted values
Note: The Kansas scenario appears to have greatest sensitivity in this form of presentation.

program details are described in RUSLE documentation (Renard et al., pending).

A previous study (Renard and Ferreira 1993) determined sensitivity of RUSLE-predicted soil loss to changes in various input-database variables. The study used the scenario of corn in a 1-year rotation on a silt loam soil, under conventional tillage conditions near Chicago, Illinois. The present work studies RUSLE response under a variety of conditions, to demonstrate the site- and condition-specific nature of model sensitivity. Focus is not on sensitivity to permutations of specific input data, but is instead on the differences of sensitivity to the permutations of the same variables for a variety of scenarios. The objective of this work is to discourage user reliance upon published sensitivity studies, and to encourage the incorporation of a sensitivity analysis into each model application study. Thus, detailed descriptions of input scenarios and associated parameter values are not given here to maintain focus on the study objectives.

Methodology

A traditional form of sensitivity analysis is Independent Parameter Perturbation (IPP), in which parameters are varied individually, usually by fixed percentages around a "base" value, and resulting response changes are analyzed. Renard and Ferreira (1993) performed a modified IPP on RUSLE. The IPP was modified to include cases of perturbing parameters (such as location) that resulted in changing suites of parameters simultaneously. The objective of this study is to show the effect of site and conditions on sensitivity results. This is accomplished by employing an IPP procedure on a variety of scenarios under which sensitivity is examined.

Scenarios. Table 1 shows the six scenarios that were designed to show model sensitivity differences among sites and conditions. The Illinois and Kansas scenarios mimic common local management practices, topography, soils, and crop characteristics. Model parameterization for these sites was done by standard procedures, with consultation from local Natural Resources Conservation Service professionals. The Georgia scenarios are simply Illinois scenarios with the location changed. This scenario

Table 1. Sites and conditions of RUSLE sensitivity scenarios

Location	Crop rotation	Tillage
Chicago, IL	Corn/soybean	Conventional
Chicago, IL	Corn/soybean	No-till
Topeka, KS	Corn/soybean/winter wheat	Conventional
Topeka, KS	Corn/soybean/winter wheat	No-till
Atlanta, GA	Corn/soybean	Conventional
Atlanta, GA	Corn/soybean	No-till

Table 2. RUSLE sensitivity scenario base locations and location permutations tested

Scenario	Base location	Permutations
Illinois	Chicago	Milwaukee, WI
		Madison, WI
		Ft. Wayne, IN
		Indianapolis, IN
		Dubuque, IA
Kansas	Topeka	Wichita, KS
		Kansas City, KS
		Dubuque, IA
		Grand Island, NE
		St. Louis, MO
		Oklahoma City, OK
Georgia	Atlanta	Greensboro, NC
		Columbia, SC
		Chattanooga, TN
		Birmingham, AL
		Montgomery, AL

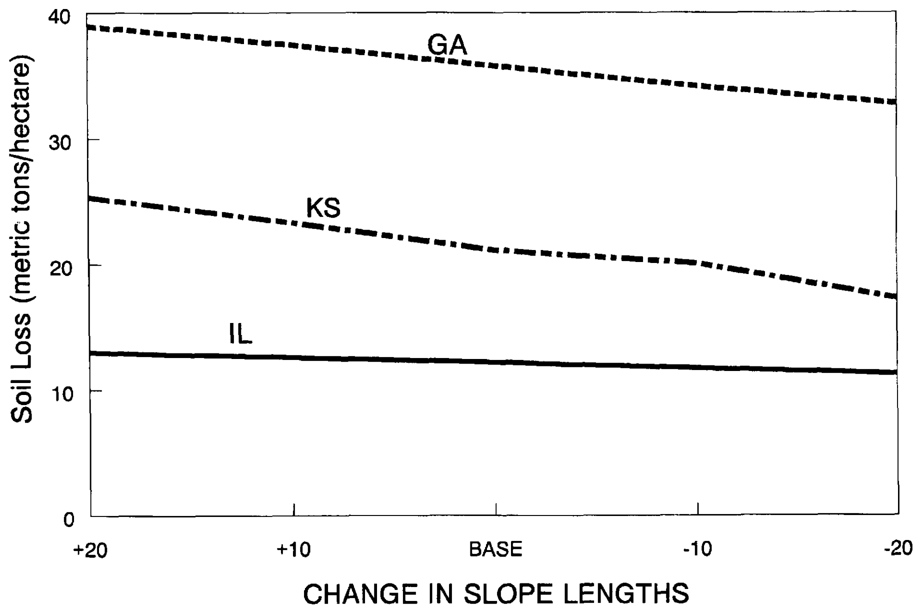

Figure 3. Responses to perturbations of slope lengths, in absolute terms of soil loss amounts

Note: Presented in this form, the Kansas sensitivity appears to be more similar to Georgia sensitivity than shown in Figure 2.

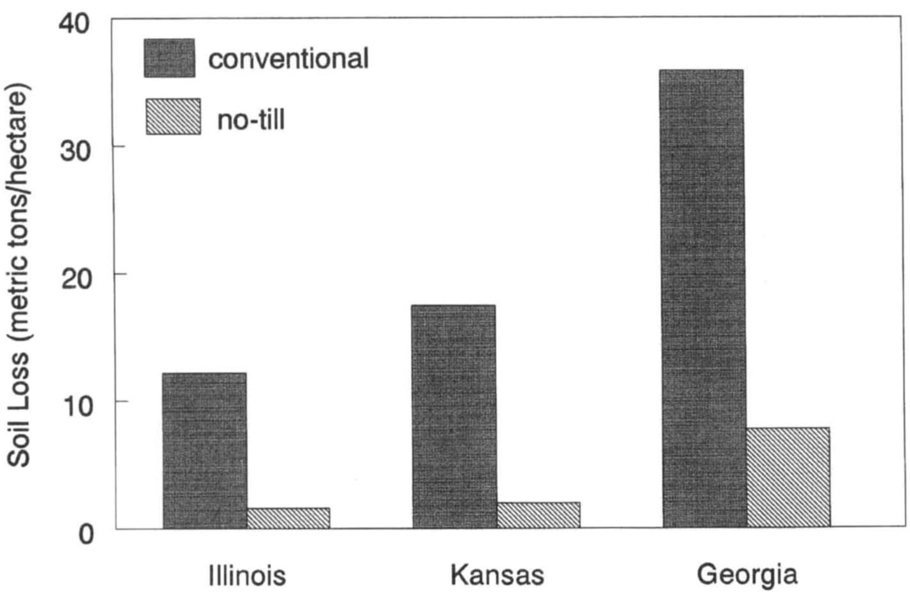

Figure 4. Contrasting soil loss from conventional tillage and no-till management scenario for three locations

TABLE 3. Scenario base value results: RUSLE factors R, K, LS, C, P and A, in metric units

Location	Scenario Rotation	Tillage	R	K	LS	C	P	A
Chicago, IL	Corn/soy	Conventional	2380	0.039	0.715	0.211	0.868	12.2
Chicago, IL	Corn/soy	No-till	2380	0.039	0.715	0.030	0.807	1.6
Topeka, KS	Corn/soy/ww*	Conventional	3230	0.035	1.780	0.150	0.710	21.4
Topeka, KS	Corn/soy/ww	No-till	3230	0.035	1.780	0.014	0.747	2.1
Atlanta, GA	Corn/soy	Conventional	5110	0.037	0.715	0.288	0.914	35.6
Atlanta, GA	Corn/soy	No-till	5110	0.037	0.715	0.063	0.905	7.7

*ww = winter wheat

Note: The metric units of these factors are: R (MJ-mm/ha-h-y); K (t-ha-h/ha-MJ-mm); A (t/ha-yr).

set was included to show the potential effect of Southern weather on erosion when all other conditions are held constant.

At each location, both conventional tillage and no-till conditions were simulated to emphasize differences in response at the same site for these two different management alternatives.

Parameter perturbations. RUSLE input includes several types of parameters: standard single-value parameters, single parameters that govern suites of related values, and parameters that may be changed individually but which are intimately related to others that should be modified simultaneously. This study includes perturbations of all three parameter types.

Location perturbations. The City Code parameter controls a data suite related to the effects of location on climate. Changing location yields a potential change of all City Database data describing the location climate, including total annual and monthly precipitation, number of freeze-free days per year, 10-year frequency daily EI, R factor, monthly temperature values, and 24 bimonthly values for the R-factor distribution. Table 2 describes perturbations to the three base scenario locations. The cities chosen are some that might be chosen by a user if the location being simulated is between database cities, a likely occurrence.

Slope length perturbations. Slope lengths at the test locations consist of three values, describing complex slopes. The base slope length values were 38m (125ft), 30m (98ft), and 38m for Illinois and Georgia and 75m (246ft), 38m, and 30m for Kansas. These multiple slope lengths were modified simultaneously at each location. All segments were varied in the same proportions—±10% and 20%.

Operation dates perturbations. Operation dates were varied as a group, assuming all management to have been shifted back and forward by 10 and 20 days. In the no-till scenarios this changed only three dates: fertilizing, planting, and harvest. The conventionally tilled scenarios are more complex, with 16 operations in Illinois and Georgia, and 14 operations in Kansas.

Cover-management code perturbations. A parameter varied individually is the Cover-Management Code, which was adjusted up and down by one code value. It should be noted that this code is only used in the P factor, but it is linked to specifications in the C factor. RUSLE offers the following Cover-Management Code options:

Code Value	Cover Management Description
1	established sod-forming grass
2	first-year grass cut for hay
3	heavy cover and/or very rough
4	moderate cover and/or rough
5	light cover and/or moderately rough

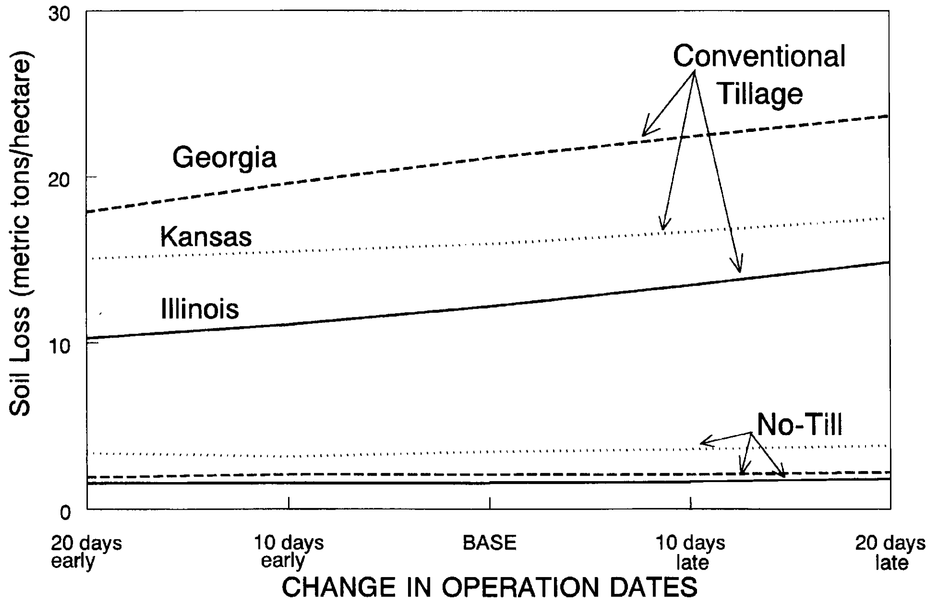

Figure 5. Effects of changes in operation dates for conventional and no-till management scenarios at three locations

Note: The more aggressive tillage of conventional management renders the soil more vulnerable to erosion

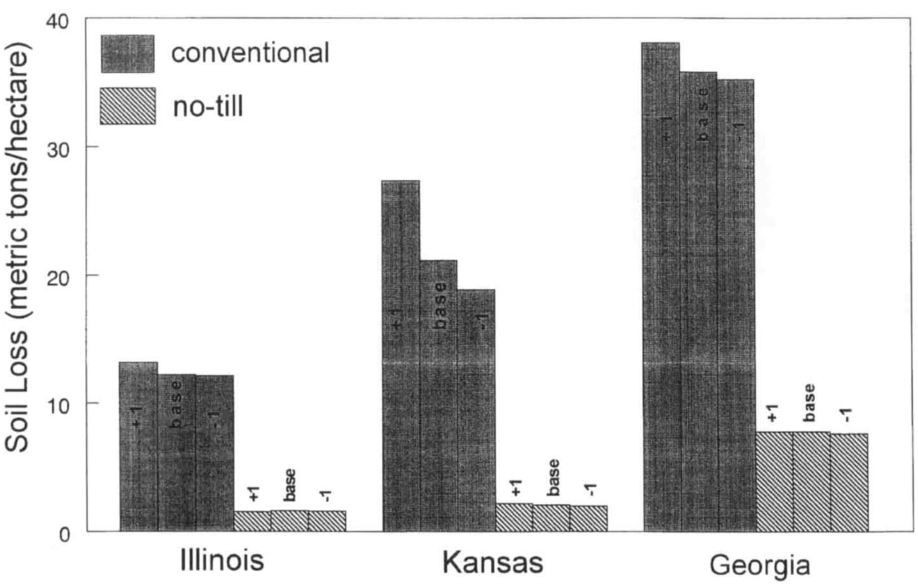

Figure 6. RUSLE responses to perturbations of base Cover-Management Codes by +1 and -1 values representing more and less cover, respectively

Note: No-till scenarios are significantly less responsive to cover management than are conventionally-tilled scenarios.

6 no cover and/or minimally rough
7 clean tilled, smooth, fallow

Erring by one code value might represent the difference between believing, for example, that the dominant condition is "moderate cover and/or rough" rather than "light cover and/or moderately rough." The Cover-Management Code represents the impacts of management on surface cover and roughness, and specifically on how these affect infiltration rates and, in turn, runoff velocities.

In summary, the parameters tested are

- location, a code that implements a suite of values describing local climate;
- slope segment length, with multiple values when describing a complex slope;
- operation dates, with associated variables (such as tillage depth) that remained unchanged; and
- cover-management code, a single-valued parameter.

Results

Table 3 summarizes results of base-value RUSLE predictions, showing variations among RUSLE factors. The most prominent feature is the order-of-magnitude difference between soil loss under conventional tillage and that under no-till at the three locations. Another is the difference between Atlanta results and Chicago results. Note that changing the location from Chicago to Atlanta changed not only the R factor, but also C and P, resulting in significantly greater soil losses under both Atlanta management schemes. Part of this magnified climatic effect is caused by increased rainfall temperature that accelerates residue loss.

Location perturbation results. Figure 1 shows the ranges of soil loss values predicted for each base location under the conventionally tilled and no-till schemes. The differences between sensitivities for the three locations demonstrates the site-specific nature of sensitivity analysis. Differences between Illinois and Kansas scenarios are net results of great differences in input data between the two locations, including soil characteristics, topography, climate, and management. Differences between Illinois and Georgia reflect sensitivity differences solely due to climate variables, because the location code is the only parameter changed between the two scenarios.

A sensitivity study employing the Kansas no-till scenario would report a range of values from –66% to +89% change from base prediction, for a spread of 155%. The conventional condition produced –44% to +62% from the base; still considerable differences, but only a 106% spread. Had the analysis been performed only with the Illinois conventional scenario, the reported soil losses would have varied by only 52%, from –24% to +28%.

Slope length perturbation. Results for conventional tillage scenarios are shown in Figure 2. No-till results are similar, but on a much smaller scale. The consistent trend is as expected: increasing slope lengths increased soil loss in all scenarios. This sensitivity is a good example of perception differences depending on presentation scheme; in this case, reporting results as % change from base, versus reporting absolute soil losses. As shown in Figure 2, the Kansas response is greater than that of the other two locations. Ranges between the ±20% changes in slope lengths vary in Kansas by almost 30%, while Georgia and Illinois ranges are on the order of 15% variation from base with ± 20% permutation. Figure 3 illustrates these responses in absolute terms (total soil loss) rather than as percentage from base values. Judging from the respective slopes on this figure, the range of Kansas values is very near that of Georgia, while Illinois appears much less sensitive in this form of presentation.

This result is important for the sake of perspective. Under the no-till condition, soil loss values in these scenarios were an order of magnitude less than under conventional tillage. An analysis showing strong sensitivity might indicate the need for careful location code selections. However, if the application is a no-till situation, the differences in response are very small, so large variations (as percentages) represent only small soil loss amounts.

Management operations perturbations. Differences between conventional and no-till scenarios demonstrate a form of operations sensitivity. Conventional tillage produced more soil loss (by an order of magnitude) than no-till at all three locations, as shown in Figure 5. Because disks, chisels, moldboard plows, and other aggressive soil-disturbing and residue-burying tools are avoided, no-till scenarios would be expected to produce less soil loss.

The effect of management timing is explored by simultaneously adjusting all operation dates. Base values were changed by ±10 and 20 days. Results are shown in Figure 5. As expected, no-till scenarios are less responsive to changes in dates, because these response changes are due to shifts only in planting, harvest, and fertilizer application dates. This changes the times of plant canopy and residue cover protection of the soil with respect to erosive rain events. In conventionally-tilled scenarios, soil vulnerability to erosion is affected not only by the timing of plant coverage, but more importantly, by the timing of soil-breaking operations such as plowing. In addition to illustrating sensitivity to operation date, Figure 5 shows the effects of conventional versus no-till management on soil loss.

Cover management code perturbation. Results of varying the cover-management code up and down one value are shown in Figure 2. The Illinois and Georgia scenarios (all corn/soybean) were comparatively insensitive to these variations. Kansas conventional tillage (under a corn/soybean/winter wheat rotation) increased 29% and decreased 11% from the base value with a code increase and decrease, respectively, while at the same location the no-till scenario showed only a ±4% difference. This is likely because the Illinois and Georgia scenarios were on flatter slopes, so changes in the cover and roughness resulting from management have less effect on runoff erosivity than they do for the steeper Kansas scenarios. The conventional-till Kansas sensitivity response is much larger than that of the other scenarios. Thus, it would be inappropriate to base parameter-choice judgements on one of these results if one is simulating the other conditions.

Conclusions

The site- and condition-specificity of sensitivity analyses are demonstrated with the RUSLE model results under both conventional tillage and no-till conditions at three locations. Sensitivity to all tested parameter perturbations was demonstrated to vary by site and condition. Data presentation format was also shown to influence perceived model sensitivity.

Future research

This study will initiate a more comprehensive sensitivity study of the RUSLE model, in which more parameters are tested, and several other scenarios are employed. For instance, crop parameter suites will be perturbed to simulate both vigorous and stunted plant growth; and attributes of various tillage implements will be modified. Southern scenarios, instead of being climate-modified Northern scenarios, are being designed to describe the system as accurately as the Northern scenarios were designed, including appropriate climate, soil, topography, and cropping and management practices.

REFERENCES CITED

Lane, L.J., and V.A. Ferreira. 1980. Chapter 6: Sensitivity Analysis. In: W.G. Knisel (ed.) CREAMS: Chemicals, Runoff and Erosion from Agricultural Management Systems. USDA–ARS Conservation Research Report No. 26.

Renard, K., and V. Ferreira. 1993. RUSLE Model Description and Database Sensitivity. Journal of Environmental Quality 22(3):458–466.

Renard, K.G., G.R. Foster, G.A. Weesies, D.K. McCool, and D.C. Yoder, Coordinators. In Press. Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE). USDA Agriculture Handbook 703.

Renard, K.G., G.R. Foster, G.A. Weesies, and J.P. Porter. 1991. RUSLE: Revised Universal Soil Loss Equation. Journal of Soil and Water Conservation 46(1):30–33.

Renard, K.G., G.R. Foster, D. Yoder, and D. McCool. 1994. RUSLE Revisited: Status, Questions, Answers, and the Future. Universal Soil Loss Equation. Journal of Soil and Water Conservation 49(3):213–220.

Wischmeier, W.H. 1976. Use and Misuse of the Universal Soil Loss Equation. Journal of Soil and Water Conservation 31(1):5–9.

Wischmeier, W.H., and D.D. Smith. 1978. Predicting rainfall erosion losses. USDA Agriculture Handbook 537, U.S. Government Printing Office, Washington, D.C.