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Assessing Changes in Soil Erosion Rates: A Markov Chain Analysis

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ABSTRACT

Markov chain analysis (one-step and long-run) is applied to the National Resources Inventory (NRI) database to evaluate changes in wind-based soil erosion rates over time. The research compares changes in soil erosion rates between NRI sample sites with and without applied conservation practices for a random sample of Great Plains counties. No significant differences between sites are found for half of the counties evaluated. The effectiveness and efficiency of conservation policies are thus questioned in light of these research results.

Key Words: *conservation, Markov, National Resources Inventory, policy, soil erosion.*

Soil erosion is the process by which earth or rocky material is worn away, loosened, or dissolved (Herren and Donahue).The wearing away of soil by wind and water is a natural process that can be accelerated by human activities such as cultivation, grazing, mining, and other commercial activities (Magleby *et al.*). Wind erosion is considered a problem because it can create immediate air pollution, has negative effects on human health and infrastructure, and reduces the long-term productivity of agricultural lands. Soil loss through water erosion also impairs land productivity and leads to increased sediment loads with subsequent negative effects on waterways and related infrastructure.

Severe soil erosion in the Great Plains of the United States during the drought years of the 1930s stimulated wind erosion research and the development of control practices (Fryrear and Lyles). Since that period the federal government has also implemented numerous incentive and regulatory programs dedicated to improving soil management, reducing soil erosion by wind (and water), and maintaining long-term soil productivity. To combat soil erosion, the U.S. Department of Agriculture's (USDA) conservation programs have used on-farm technical assistance, extension education, cost-sharing assistance, and rental or easement payments to take land out of production and put it into conservation uses (Magleby *et al.*). Soil conservation has also been linked to federal crop subsidies through Conservation Compliance provisions.

Federal involvement in soil conservation efforts began with the creation of the Soil Conservation Service in 1935, reached a high point during the Soil Bank Program (initiated in 1956), continued through a series of Clean Water Acts through the 1970s and 1980s, and reached another relatively high level with the advent of the Conservation Reserve Program (CRP) in 1985. Conservation Compliance, Sodbuster and Swampbuster provisions were

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also initiated in the 1985 farm bill. In 1994, approximately $4 billion were spent on conservation efforts by the USDA and other state and local agencies (Magleby *et al.*). The Conservation Reserve Program accounted for approximately one-half of the 1994 expenditures. In 1995 the USDA was administering 17 programs giving land users financial incentives to apply conservation measures to their farms, ranches, and forests (U.S. General Accounting Office 1995). These programs were supporting conservation measures on 71 million crop, range, and forest acres under about 565,000 agreements with land users (U.S. General Accounting Office 1995).

National Resources Inventory data show average overall reductions in soil erosion rates for all cropland categories (in tons/acre/year) between 1982 and 1992 (Kellogg, TeSelle, and Goebel). Soil loss from wind and water erosion on cropland is reported to have dropped from a total of 3.1 billion tons on 421 million acres in 1982 to 2.1 billion tons on 382 million acres in 1992 (USDA–Natural Resources Conservation Service 1995). Conservation policies have been credited for the reduced soil erosion (Kellogg, TeSelle, and Goebel; Magleby *et al.*) and for generating numerous other benefits (e.g., increased soil productivity, improved water and air quality, enhanced wildlife habitats, etc.) (Young and Osborn; Magleby *et al.*; Ribaudo *et al.*).

There exist many unanswered questions regarding the benefits or costs avoided as a result of conservation, and the financial costs of reducing soil erosion (Young, Walker, and Kanjo; U.S. General Accounting Office 1993). The actual estimates of soil loss by wind and water erosion have also been questioned and have led to recent efforts to reformulate the Universal Soil Loss Equation (for water erosion) and the Wind Erosion Equation (WEQ). But even in the presence of uncertain estimates of both soil losses and the benefits of conservation policies, it appears there will continue to be commitment of public funds to reducing soil erosion, as evidenced by the numerous conservation provisions within the 1996 Federal Agricultural Improvement and Reform Act. This commitment is likely to be accompanied by a larger government role in agricultural land management decisions. Given this setting, more evaluation of the impacts of soil conservation programs is merited. Additional research on the efficiency and effectiveness of soil conservation efforts could be a valuable input into conservation and agricultural policy debates.

Data

Concern over natural resource trends in the U.S. has been the primary driving force behind an intensive, comprehensive data collection effort conducted by the USDA Natural Resources Conservation Service (formerly the Soil Conservation Service). This data collection effort is called the *National Resources Inventory* (NRI). The NRI is congressionally mandated, national in scope, and dedicated to providing a record of the nation's conservation accomplishments and future program needs. The inventory is conducted every five years (since 1977) to determine the status, condition, and trends for soil, water, and related resources (USDA–Natural Resources Conservation Service 1994). The data provide a snapshot of resource conditions at the time they are collected.

The NRI database is a statistically representative inventory of land cover and use, soil erosion, prime farmland, wildlife habitat, and other natural resource variables on non-Federal, rural land. There are over 800,000 sample sites nationwide with the number of sites varying between states. For example, there are 76,338 sample sites in Texas; 57,874 in Kansas; and 12,513 in Wyoming (USDA–Natural Resources Conservation Service 1994). The data are based on recognized statistical sampling methods and are statistically reliable for national, regional, state, and substate analysis (USDA–Natural Resources Conservation Service 1994). At each sample point, information is currently available from three data collection years-1982, 1987, and 1992 (USDA–Natural Resources Conservation Service 1998b). These data are in CD-ROM format and can be analyzed using standard PC-database software.

Data for the 1997 NRI are expected to be available sometime in 1999.

The NRI database for 1982, 1987, and 1992 has been and will continue to be used for conservation and agricultural policy deliberations. In fact, a primary use of NRI data has been in the area of policy impact analysis. The NRI provided information used in the development of the Conservation Reserve Program, Conservation Compliance, Sodbuster, and Swampbuster provisions of the Food Security Act of 1985 (USDA–Natural Resources Conservation Service 1994). NRI data are used as evidence that federal conservation programs have been successful in reducing erosion in the United States (Kellogg, TeSelle, and Goebel; Magleby *et al.*). From NRI data it has been concluded that average soil erosion rates nationwide fell between 1982 and 1992. It is estimated that 72 percent of the soil savings came from reductions in erosion on highly erodible land, with wind erosion rates on cropland decreasing nearly 25 percent between 1982 and 1992 (USDA–Natural Resources Conservation Service 1995). NRI documentation concludes that much of the reduction in soil erosion is attributable to "efforts by the nation's farmers in response to conservation provisions in the 1985 Farm Bill" (USDA–Natural Resources Conservation Service 1994). Magleby *et al.* state that "U.S. conservation programs have reduced erosion on both a total and a per-acre basis."

Wind erosion rates for 1982, 1987, and 1992 were predicted using the wind erosion equation (WEQ) which was published in its present form in 1965 (Woodruff and Siddoway). Field application of the WEQ has evolved since 1965; however, the form of the equation has remained the same since that time (Argabright). A new erosion prediction method to replace the WEQ (e.g., the Wind Erosion Prediction System (WEPS)) has been under development for several years, although use of the old WEQ was continued for the 1997 NRI data collection (Wind Erosion Research Unit–Kansas State University).

The WEQ is designed to predict long-term average annual soil losses from a field having specific characteristics (USDA–Natural Resources Conservation Service 1998a). The equation is $E = f(I, K, C, L, V)$, where E is the potential average annual soil loss in tons/acre/year, I is the soil erodibility index based in texture and aggregation, K is the soil ridge or surface roughness factor, C is the climate factor (windspeed and soil moisture), L is the unsheltered distance across the field or the effect of field size or length, and V is the quantity of vegetative cover calculated from tables according to the kind of cover (stubble, cut residues) left on the field (Wind Erosion Research Unit–Kansas State University; Herren and Donahue; Donahue, Miller, and Shickluna). The relevant I, K, C, and L factors are combined multiplicatively to derive a first estimate of erosion, which is then adjusted by the vegetative cover to derive the final value of E (Donahue, Miller, and Shickluna). By comparison, the elements of the Universal Soil Loss Equation (USLE) for estimating average annual soil loss from sheet and rill erosion (A) are rainfall (R), soil erodibility (K), slope length (L), slope degree (S), cropping practice (C), and conservation practice (P).

Although the full NRI is conducted every five years, the currently available data set includes the WEQ's K, L, and V factors for 1979–1982, 1984–1987, and 1989–1992. These factors include the current year's values (e.g., 1982, 1987, and 1992) and historical data for the three years preceding each data collection year. The WEQ's C and I factors vary between data collection sites based on local conditions, although at each site these factors are held constant for all years for which the WEQ is calculated. The NRI data set includes E estimates for all the years listed above, with variation as a result of changes in K, L, and V. The year-to-year differences are due primarily to crop rotations. NRI wind erosion data are thus very different from NRI predictions of soil loss rates due to water erosion (in tons/acre/year) using the USLE, which are currently available for only 1982, 1987, and 1992.

Hypotheses

Like many other natural or biological processes, soil erosion by wind exhibits both dependency and randomness between years. If a site has a relatively low rate of soil loss due to wind erosion in any given year (n), then one would expect that soil loss conditions in $n + 1$ would not be significantly different. However, severe changes in weather conditions (such as the onset of a drought combined with windstorms) would be expected to increase erosion rates, particularly if no conservation practices have been undertaken. Implementation of soil conservation practices would be expected to decrease or stabilize erosion rates and aid in preventing increases in erosion rates. Thus, if the rates of soil loss by wind erosion over time at similar sites are compared, we would expect differences in wind erosion between sites where conservation practices have been applied and sites where no conservation practices have been implemented.

A Probabilistic Model of Soil Erosion Rates by Wind

A first-order Markov process is a stochastic process in which the probability of an event in n depends on events in $n - 1$. The probability that a process will move from state i to state j between two periods of time is designated as P_{ij}. Assuming the variable of interest is the rate of soil erosion by wind, the finite Markov chain process requires that r different soil erosion rates be defined and that movements between these soil loss categories over time be summarized in a soil loss flow or transition matrix (Vandeveer and Drummond). Once the matrix for soil erosion is defined, the probability (P_{ij}) of moving from one soil erosion rate (S_i) to another soil erosion rate (S_j) is computed as:

$$(1)\qquad P_{ij} = S_i \Big/ \sum_i S_{ij}.$$

Each P_{ij} represents the percentage of sites that started in soil loss category S_i in period n and moved to soil loss category S_j in the following period. For example, P_{11} represents the proportion of sites that started in S_1 in time n and continued in S_1 in time $n + 1$, P_{12} represents the proportion of sites that moved between S_1 and S_2 between n and $n + 1$. One-step transition probabilities can be estimated by determining the proportion of times that the rate of soil loss at sample sites moved from one state to every other state defined. With three rates of soil loss defined for the problem: low = 1, medium = 2, and high = 3, the transition probability matrix would be:

$$(2)\qquad P = \begin{bmatrix} P_{11} & P_{12} & P_{13} \\ P_{21} & P_{22} & P_{23} \\ P_{31} & P_{32} & P_{33} \end{bmatrix}.$$

Transition probability matrices for different sets of sites or observations can be compared using a test statistic presented by Anderson and Goodman. This statistic evaluates whether the sequence of changes from different sites or samples are from the same Markov chain. The test statistic is distributed as a χ^2 with $m(m - 1)$ degrees of freedom for a first-order Markov chain. The test statistic is:

$$(3)\qquad \chi^2 = \sum_i \sum_j \frac{1/C_{ij}(P_{ij}^{(1)} - P_{ij}^{(2)})^2}{P_{ij}^{*}},$$

where $P_{ij}^{(h)}$ is the P_{ij}^{th} element in the transition probability matrix from sample h (1 or 2), $P_{ij}^{(*)}$ is the P_{ij}^{th} element when pooled across both samples, C_{ij} is $1/n_{ij}^{(1)} + 1/n_{ij}^{(2)}$, $n_{ij}^{(h)}$ is the number of $i \rightarrow j$ sequence changes observed for sample h, and m is the size of the $m \times m$ transition matrix.

The null hypothesis (H_0) for the test is that there is no difference between transition probability matrices. If we fail to reject H_0 we can conclude that the two matrices being compared are not statistically different.

With the recursive property of the Markov chain, n-step (or long-run) transition probability matrices can be computed. The n-step matrix can be used to address questions regarding the probability of finding an erosion rate in state i in n years. Calculation of the n-step matrix is accomplished by multiplying the matrix of one-step transition probabilities by itself or

$$(4)\qquad P^{(n)} = P \cdot P \cdots P = P^{(n)} = PP^{n-1}.$$

One important result related to the long-run behavior of Markov processes is that there is a limiting probability the system will be in state *j* after a large number of transitions, and this probability is independent of the initial state (Hillier and Lieberman). These are the steady-state probabilities which occur when a matrix of one-step probabilities is multiplied by itself enough times such that each of the probability matrix rows has identical entries. Transition probability matrices that have 0 or 1 elements will never fully arrive at the steady-state, due to the recurrent nature of the 0 and 1 states. The Anderson-Goodman test can also be applied to test for differences between long-run transition probability matrices.

Methods

Aandahl defined over 600 counties in the Great Plains region. Counties in extreme South Texas, rocklands, and desert areas of southwestern New Mexico were eliminated from Aandahl's list, leaving a sampling frame of 554 counties. Fifty percent (277) of these counties were randomly selected for analysis using the procedures outlined above. The sample was proportional by state. The data for 64 counties could not be analyzed because there were no NRI observation points for either the with or without conservation practices matrix, or because there were no transitions between erosion levels over time. Data for 215 counties with NRI observation points with conservation practices and without conservation practices were subjected to the Markov chain analysis.

The three rates of soil loss by wind erosion (e) were defined as (where tay = tons/acre/year): low = 1 ($e \leq 5$ tay), medium = 2 ($5 < e \leq 15$ tay), and high = 3 ($e > 15$). A soil's T-value is the amount of soil which can be lost annually due to erosion with no significant reduction in productivity. For most soils, T is about five tay (Osborn and Heimlich). The first sign-up periods for CRP targeted croplands where soil erosion was above three times the soil loss tolerance rate ($3T$) (Dicks and Coombs), while the average erosion reduction for land enrolled in the CRP was 19 tay (Lindstrom, Schumacher, and Blecha). The 1–3 scale used in this analysis was thus designed to include the range of soil loss from low rates to rates which have been considered severe enough for significant policy responses.

For each of the sampled counties, the NRI database was filtered to extract sample sites for which the primary use (*PRIMUSE*) was classified as "Agricultural—food, feed, fiber, seed." The next step in data manipulation was to separate (for each county) the sample sites meeting the primary use criteria into two subsets. The subsets were for sites where the NRI data indicate conservation practices had been applied in 1982 or 1987 and sites where no conservation practices are recorded as applied for those years. Conservation practices typically used to reduce soil loss by wind in the Great Plains region and noted in the NRI database as having been applied in the counties analyzed were primarily conservation tillage, contour farming, wind stripcropping, filter stripping, conservation cover, planned grazing systems, and proper grazing use. The NRI data for conservation practices provide no information as to whether or not any emergency tillage was undertaken to reduce soil loss during critical wind erosion events.

After the sample sites had been separated into the two subsets (*Conservation Practices* and *No Conservation Practices*), the data for each county were subjected to transition analysis over the period 1979–1992. There were 12 observation points over that period (1979–1982, 1984–1987, and 1989–1992); thus there were 11 transitions. The one-step transition probabilities were estimated by determining the proportion of times that soil losses by wind erosion moved from one state to another (e.g., $1 \rightarrow 1$, $1 \rightarrow 2$, $1 \rightarrow 3$). After the two transition matrices (e.g., *Conservation Practices* and *No Conservation Practices*) for each county were calculated, the χ^2 test was performed to evaluate whether the two transition matrices were from the same Markov chain.

Long-run transition probability matrices also were calculated using the procedures explained above. The *Conservation Practices* and *No Conservation Practices* one-step matrices for each county were multiplied by

Table 1. Example one-step Markov transition probability matrices for *No Conservation Practices* sites and *Conservation Practices* sites

No Conservation Practices				Conservation Practices				No Conservation Practices				Conservation Practices			
state i/j	1	2	3	state i/j	1	2	3	state i/j	1	2	3	state i/j	1	2	3
Roosevelt County, New Mexico: χ^2 = 4.28								**Yuma County, Colorado: χ^2 = 60.74**							
1	.77	.10	.13	1	.77	.11	.12	1	.55	.17	.28	1	.90	.06	.04
2	.14	.67	.19	2	.14	.72	.14	2	.31	.40	.29	2	.24	.68	.08
3	.08	.13	.79	3	.19	.10	.71	3	.43	.20	.37	3	.13	.08	.79
Scott County, Kansas: χ^2 = 5.56								**Garfield County, Montana: χ^2 = 17.71**							
1	.69	.20	.11	1	.79	.18	.03	1	.43	.30	.27	1	.68	.14	.18
2	.74	.26	.00	2	.78	.19	.03	2	.88	.12	.00	2	.61	.28	.11
3	.42	.00	.58	3	.49	.14	.37	3	.84	.10	.06	3	.68	.04	.28
Dawson County, Texas: χ^2 = 1.13								**Cimarron County, Oklahoma: χ^2 = 22.39**							
1	.55	.00	.45	1	.60	.00	.40	1	.85	.15	.00	1	.83	.10	.07
2	.04	.66	.30	2	.02	.85	.13	2	.10	.89	.00	2	.15	.73	.12
3	.01	.01	.98	3	.00	.02	.98	3	.00	.03	.97	3	.17	.15	.68

themselves up to 50 times. Some matrices arrived at the steady-state after as few as eight iterations, although when the matrices had 0 or 1 elements, the steady-states were not reached. The χ^2 test was performed to evaluate whether the two long-run transition matrices for each county were from the same Markov chain.

Findings

Examples of one-step Markov transition matrices for a few of the 215 counties analyzed are shown in Table 1. Table 2 presents a summary of findings for all 215 counties. To illustrate, the *No Conservation Practices* matrix for Roosevelt County, New Mexico indicates

Table 2. Summary of one-step Markov chain analysis results by state for sampled Great Plains counties

		Results of Analysis Sorted by Significance Level				
		Results Significant at P =				
State	Sampled Counties	.95	.90	.75	Not Significant	Insufficient Data*
Colorado	11	6	1	0	3	1
Kansas	36	7	1	2	16	10
Montana	22	7	2	0	11	2
North Dakota	30	2	1	2	25	0
Nebraska	53	9	3	1	25	15
New Mexico	10	1	0	0	4	5
Oklahoma	24	1	4	0	8	11
South Dakota	39	4	8	3	24	0
Texas	45	5	3	1	21	15
Wyoming	7	1	0	0	1	5
Total	277	45	23	9	138	64
(%)	(100.00%)	(15.52%)	(8.30%)	(3.25%)	(49.82%)	(23.10%)

* These counties did not have any sampled sites for either the *No Conservation Practices* or the *Conservation Practices* matrix or had no transitions between erosion rates over time

if a site had a low rate of soil loss by wind erosion in a given year, there was a 77-percent probability it would have a low rate of soil loss by wind erosion in the next year (P_{11}) (Table 1). If there was a medium rate of soil loss in a given year, the probability that soil loss the next year would be high (P_{23}) was 19 percent. The matrix elements along the main diagonal of this matrix are relatively high, implying some stability in erosion rates from one year to the next. The transition matrix for sites in Roosevelt County where *Conservation Practices* were applied is also quite stable, although some differences between it and the previous matrix are evident. For instance, when conservation practices are applied, the probability a site will go from having a high rate of soil erosion to a low rate is 19 percent (P_{31}). P_{31} for the *No Conservation Practices* matrix was 8 percent. Other differences between the two matrices exist; however, most are relatively small. The χ^2 test statistic with six degrees of freedom and $P = 0.95$ is 4.28. Thus, with a critical value of 12.59, we fail to reject H_0 for Roosevelt County and conclude that the two matrices are not statistically different.

The two transition matrices for Scott County, Kansas are also not significantly different from each other ($\chi^2 = 5.56$). Based on the diagonal values, the *Conservation Practices* matrix appears to be slightly less stable than the *No Conservation Practices* matrix for this county. But, even with this difference H_0 cannot be rejected for Scott County, Kansas.

In the case of Dawson County, Texas, the probability a site will have a high rate of erosion from one year to the next (P_{33}) is 98 percent regardless of whether conservation practices are applied or not. Other diagonal elements of the two Dawson County matrices are also relatively high, indicating stability in soil erosion rates over time in both cases. Again, H_0 cannot be rejected for this county with $\chi^2 = 1.13$, and we can conclude that the two transition matrices are not significantly different.

For Yuma County, Colorado, there is a 79-percent probability a high rate of erosion site will have high rates from one year to the next with *Conservation Practices,* while P_{33} for *No Conservation Practices* sites is 37 percent. Yuma County is one of the analyzed counties where the two transition matrices are statistically different ($\chi^2 = 60.74$). However, that result does not appear to allow the blanket conclusion that conservation practices made a positive difference in reducing soil erosion rates from one year to the next in Yuma County. The Yuma County transition matrix for sites where conservation practices have been applied appears more stable than the *No Conservation Practices* matrix (because of the larger magnitude of the diagonal elements of the transition matrix). But comparison of several matrix elements (e.g., P_{33}, P_{32}, and P_{31}) raises questions about the effects of conservation practices from one period to the next.

For instance, in the absence of conservation practices the probability a site with a high rate of soil erosion will drop to a medium rate (P_{32}) is 20 percent, and the probability of a drop from high to low (P_{31}) is 43 percent in Yuma County. Both P_{32} and P_{31} are higher than the same matrix elements for the *Conservation Practices* matrix. For many of the counties analyzed, these elements are larger with conservation practices than without conservation practices, as would be expected if conservation practices reduce erosion rates. However, an exception is noted for Yuma County. In support of the notion that conservation practices work to stabilize soil loss rates, P_{11} for Yuma County is 90 percent with conservation practices, but 55 percent for sites with no conservation practices.

The one-step *Conservation Practices* and *No Conservation Practices* transition probability matrices for Garfield County, Montana and Cimarron County, Oklahoma are also significantly different. The Garfield County *Conservation Practices* matrix appear to be more stable than the *No Conservation Practices* matrix, as evidenced by the larger diagonal elements. The Cimarron County matrices are both quite stable, with similar diagonal elements; however, the *No Conservation Practices* matrix has several zero elements which contribute to a χ^2 test value above the critical level.

Table 3. Example long-run Markov transition probability matrices for *No Conservation Practices* sites and *Conservation Practices* sites

No Conservation Practices				Conservation Practices				No Conservation Practices				Conservation Practices			
state i/j	1	2	3	state i/j	1	2	3	state i/j	1	2	3	state i/j	1	2	3
Roosevelt County, New Mexico: χ^2 = 16.48								**Yuma County, Colorado: χ^2 = 17.89**							
1	.31	.26	.43	1	.43	.27	.30	1	.45	.23	.32	1	.64	.16	.20
2	.31	.26	.43	2	.43	.27	.30	2	.45	.23	.32	2	.64	.16	.20
3	.31	.26	.43	3	.43	.27	.30	3	.45	.23	.32	3	.64	.16	.20
Scott County, Kansas: χ^2 = 9.43								**Garfield County, Montana: χ^2 = 2.26**							
1	.66	.17	.17	1	.78	.18	.04	1	.60	.23	.17	1	.67	.14	.19
2	.66	.17	.17	2	.78	.18	.04	2	.60	.23	.17	2	.67	.14	.19
3	.66	.17	.17	3	.78	.18	.04	3	.60	.23	.17	3	.67	.14	.19
Dawson County, Texas: χ^2 = 1.09								**Cimarron County, Oklahoma: χ^2 = 61.02**							
1	.02	.04	.94	1	.01	.10	.89	1	.40	.60	.00	1	.49	.29	.22
2	.02	.04	.94	2	.01	.10	.89	2	.40	.60	.00	2	.49	.29	.22
3	.02	.04	.94	3	.01	.10	.89	3	.39	.58	.03	3	.49	.29	.22

In almost 50 percent of the sampled counties, H_0 could not be rejected at $P = 0.75$ (Table 2). H_0 was rejected at $P = 0.75$ in 27.07 percent of the counties in the sample, while sufficient data were not available to analyze almost a fourth of the selected counties.

Examples of long-run *Conservation Practices* and *No Conservation Practices* transition probability matrices are presented in Table 3. The steady-state was reached in five of the six example counties. In all these cases, the data for the three rows of both the *Conservation Practices* and the *No Conservation Practices* matrices have identical entries. This implies the probability of being in state *j* after many years is independent of the initial state.

The long-run results for Dawson County, Texas indicate that regardless of the initial rate of soil erosion (low, medium, or high), there is a high long-run probability of a high rate of erosion. This outcome is very likely on sites with and without conservation practices, and is not surprising given soil characteristics and cotton production in that region. Consequently, the two long-run matrices for Dawson County are not significantly different from each other ($\chi^2 = 1.09$). H_0 cannot be rejected for Garfield County ($\chi^2 = 2.26$), and we can conclude that these two transition matrices also are not significantly different.

H_0 could not be rejected for the Roosevelt County, New Mexico one-step matrices; however, the hypothesis of similar long-run matrices can be rejected at the highest level of significance ($\chi^2 = 16.48$). In the long run, regardless of the initial state with *Conservation Practices* the probability of a low rate of erosion is 43 percent, a medium level is 27 percent, and a high level is 30 percent. The *No Conservation Practices* matrix shows the opposite, with the high level of erosion having the highest probability. The outcomes of the analysis for Roosevelt County and for Yuma County, Colorado lend support to the notion of effective conservation policies. In Yuma County, the null hypothesis that the long-run *No Conservation Practices* and the *Conservation Practices* transition probability matrices are not significantly different also can be rejected ($\chi^2 = 17.89$). With conservation practices, there is a 64-percent probability of a long-run low rate of erosion regardless of the initial state. The *No Conservation Practices* matrix has a 43-percent probability of a long-run low rate of erosion.

The long-run matrix for Cimarron County,

Table 4. Summary of long-run Markov chain analysis results by state for sampled Great Plains counties

State	Sampled Counties	Results of Analysis Sorted by Significance Level: Results Significant at P = .95	.90	.75	Not Significant	Insufficient Data*
Colorado	11	2	1	2	5	1
Kansas	36	7	2	2	15	10
Montana	22	11	2	2	5	2
North Dakota	30	2	0	0	28	0
Nebraska	53	11	2	0	25	15
New Mexico	10	5	0	0	0	5
Oklahoma	24	5	1	0	7	11
South Dakota	39	6	2	0	31	0
Texas	45	13	3	1	13	15
Wyoming	7	1	0	0	1	5
Total (%)	277 (100.00%)	63 (22.74%)	13 (4.69%)	7 (2.53%)	130 (46.93%)	64 (23.10%)

* These counties did not have any sampled sites for either the *No Conservation Practices* or the *Conservation Practices* matrix or had no transitions between erosion rates over time.

Oklahoma did not reach a steady-state due to the recurrent nature of the zero states. However, it can be observed that in the long run, the probability of a medium level of erosion is highest, regardless of the initial state under conditions of *No Conservation Practices.* With *Conservation Practices,* the probability of a low level of erosion is highest.

H_0 could not be rejected at $P = 0.75$ in 46.9 percent of the counties analyzed over the long run (Table 4). In 29.96 percent of the counties, the conclusion can be made that the *Conservation Practices* and *No Conservation Practices* matrices are significantly different, with H_0 rejected at $P = 0.75$. Again, 64 counties could not be analyzed.

Discussion

The results of this preliminary research effort are intriguing and raise several questions. On one hand, the nature of the NRI data (specifically the WEQ values) may be such that this research is an example of garbage in, garbage out. If the NRI data are invalid and do not accurately report soil loss rates by wind erosion in the Great Plains counties tested (and possibly throughout the rest of the U.S.), then the results of this analysis are invalid. However, the NRI data have been an important input in conservation and related agricultural policy debates and analyses over the last several years. The NRI data are used to support claims that conservation policies have worked. Therefore, the conclusion is made that public and private expenditures and the effort that are inputs into conservation practices have paid off. The regulatory direction in which agricultural and resource management policies have taken in recent years has also been justified by NRI data. The results presented here lead us to approach those conclusions with caution.

Kellogg, TeSelle, and Goebel indicate that nearly one billion tons of soil savings occurred annually between 1982 and 1992 because of reductions in wind and water erosion rates. They state that about 40 percent of the savings were due to enrollment of land in the CRP, 54 percent because of other government programs and voluntary efforts of farms, and about 6 percent due to the conversion of land. The authors discuss average erosion rates and do not discuss or compare changes in erosion rates on lands where conservation practices have been applied (as a result of being enrolled in a program or not), and lands where no conservation practices have been implemented. A

Table 5. Changes in erosion rates for NRI sites in sampled Great Plains counties, 1982–1992

	Sampled Counties' Erosion Rate Changes (1982–1992) for NRI Sample Sites *With Conservation Practices*:				Changes in Sampled Counties' Erosion Rates (1982–1992) for NRI Sample Sites *Without Conservation Practices*:			
State	# NRI Sample Sites	% Increased	% No Change	% Decreased	# NRI Sample Sites	% Increased	% No Change	% Decreased
Colorado	781	30.2	30.2	39.6	441	32.0	24.3	43.7
Kansas	4,384	40.7	22.9	36.4	1,155	44.8	18.3	36.9
Montana	1,125	37.2	21.5	41.3	553	34.7	16.3	49.0
North Dakota	4,054	15.3	30.1	54.6	2,657	13.4	28.8	57.8
Nebraska	3,676	26.9	52.4	20.7	880	32.1	37.5	30.4
New Mexico	193	55.1	12.3	32.6	195	55.4	6.1	38.5
Oklahoma	1,034	32.7	29.8	37.5	232	30.6	27.6	41.8
South Dakota	2,445	35.5	24.2	40.3	2,327	34.6	14.2	51.2
Texas	1,672	21.2	28.1	50.7	470	21.7	28.5	49.8
Wyoming	199	42.7	35.2	22.1	16	37.5	37.5	25.0

cursory examination of changes in erosion rates (i.e., the WEQ) reported by the NRI between 1982 and 1992 is presented in Table 5. WEQ values for sampled Great Plains counties subjected to the Markov chain analysis were categorized as increased (i.e., 1992 > 1982), no change (1992 = 1982), or decreased (1992 < 1982). The data in Table 5 are not weighted by land area (thus no estimate of aggregate soil savings is presented), and are only for the sampled counties subjected to the Markov chain analysis. However, from Table 5 it is apparent that erosion rates in the sampled counties did not all decrease between the 1982 and 1992 data collections.

The Markov chain analysis of NRI data reported here does not reject the Kellogg, TeSelle, and Goebel report of reductions in (some) wind erosion rates between 1982 and 1992. These WEQ assessments come directly from the NRI database, with the aggregate estimates of soil savings calculated by multiplying the number of acres for a land type by the change in average erosion. However, this research creates new questions regarding erosion rates which (according to the NRI database) did not decrease over the period of analysis. Associated aggregate soil losses must also be looked at differently in light of the approach to the NRI database taken in this research. For instance, what would have been the changes in WEQs and aggregate soil losses which would have occurred in the absence of government programs? Or, how much of the WEQ and soil loss reductions estimated for the period 1982–1992 occurred on lands not influenced by programs or Conservation Compliance provisions?

Unfortunately, no economic or financial variables in the NRI allow for site-specific evaluation of relationships between expenditures for soil conservation and changes in erosion rates. This paper thus does not provide a direct economic policy analysis; however, the results are useful in examining the effectiveness and thus efficiency of conservation policies. If changes in rates of soil erosion due to wind are as random *or* as stable as suggested by the results of the Markov chain analysis of NRI data, the purported payoffs from public investments to reduce wind erosion must be questioned. Furthermore, in the more arid areas of the Great Plains, cropping may produce soil losses in excess of regeneration rates even under the best of climatic and topographic conditions (Bunn). Therefore, policy measures designed to reduce soil losses by wind erosion in areas such as the Southern High Plains (e.g., Roosevelt County, NM or Dawson County, TX) may be regularly subject to failure regardless of the conservation technologies employed.

The Markov chain research was conducted using counties as the unit of analysis. This method of aggregation is the most straightforward way of approaching the NRI database, as the data are organized such that each county has a unique five-digit identifier. Data are further organized by state and region of the country. Aggregation of the data by similar soil types, subregions, or land resource areas might provide additional insight into the results obtained here. Each NRI sample site (28,489 of which were used in this analysis) has information for soil series, soil texture, slope, land capability class, and other factors which could be used to stratify the data. The data could also be stratified by the elements of the WEQ (i.e., I, K, C, L, V). The Markov chain analysis could then be conducted for the different aggregations of data. This expansion of the current research would assist in addressing the question of whether conservation measures are more effective when used with a particular soil and crop combination. The use of counties as the unit of analysis in this first Markov chain manipulation of the NRI data is limited because soil characteristics clearly do not match political boundaries. However, differences in soils, their erodibility, and effectiveness of conservation measures between regions or states (i.e., West Texas vs. North Dakota) can be inferred from the results presented here.

The NRI data are currently being updated for 1997. This new database will cover the period during which program-crop farmers implemented Conservation Compliance plans (e.g., 1990–1995). It will be interesting to continue the analysis of transitions between rates of soil losses by wind across the additional years that will be included in the updated database. If these results indicate no significant differences between sites with *Conservation Practices* and *No Conservation Practices*, there will be further cause to question both public investment returns and increased regulation as a result of Conservation Compliance. Markov chain analysis conducted for different aggregations of the updated data (i.e., soil types, subregions, etc.) would also provide greater insight into the effectiveness of more recent conservation policies.

Conclusion

An alternative analytical procedure has been applied to the NRI data and results indicate that for a randomly selected sample of Great Plains counties with a wide range of soils and climates, changes in soil erosion rates (due to wind) over time may have less relationship to conservation practices than is often concluded from earlier straight time-series reviews of the data. Approximately half of the counties analyzed showed no differences between *Conservation Practices* and *No Conservation Practices* transition matrices for the years evaluated. However, it is unknown if most of the matrices for the analyzed counties are not significantly different from each other *due to* conservation practices or *in spite of* conservation practices.

One method to examine this question of causality is to regress the transition probabilities on factors assumed to account for differences in the probabilities. The impact of specific conservation practices, geographic location, or physical characteristics of the NRI sample sites (to the extent that this information is included in the NRI) could be analyzed using multiple regression. The relationship between transition probabilities and the elements of the WEQ (i.e., I, K, C, L, V) could also be examined in a regression framework. This expansion of the research would help to determine if the results for the transition matrix probability analysis reported here are explained by or related to identifiable factors.

The Markov chain analysis described here could also be expanded to examine expected economic returns on lands with and without applied conservation practices. With every transition $i \rightarrow j$, there is an associated payoff (i.e., a reward or a loss, an R_{ij}). Identification of the R_{ij}'s in this application would likely involve assessment of the productivity impacts of changes in soil erosion rates. This analysis would entail the computation of different expected returns for each state of soil loss.

To date, the NRI database has not been extensively explored by economists. As mentioned above, the data set is not particularly amenable to economic or financial analysis. It is hoped that this research will prompt other social scientists to examine and use the NRI data to address past and future questions dealing with conservation policies.

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