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A Farm-Level Analysis of Soil Loss Control: Modeling the Probabilistic Nature of Annual Soil Loss

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The Conservation Compliance provision of the Food Security Act of 1985 requires all farmers who farmed highly erodible land prior to the passage of the Act to have a locally approved conservation plan fully implemented by 1995 or lose eligibility for numerous farm programs. Soil loss estimates of various crop, tillage practices, and conservation practices, however, are stochastic in nature. A farm planning model is suggested that allows for stochastic soil loss estimates. The model is compared to other models used in farm level soil conservation studies. The model shows promise as a more acceptable tool in that the farm plans are more likely to be acceptable to the farmer.

Introduction and Problem Statement

The Conservation Compliance provision of the Food Security Act of 1985 (hereafter referred to as the Provision) requires all farmers who farmed highly erodible land prior to the passage of the Act to have a locally approved conservation plan for those highly erodible acres by 1990.¹ Furthermore, the conservation plan must be fully implemented by 1995. Failure to meet either of these deadlines will result in a loss of eligibility for numerous farm programs, at least until the farmer meets the requirements.²

The Provision stipulates that soil loss on the highly erodible acreage must be no greater than the soil tolerance level. The process of erosion, however, is inherently stochastic due to the influence of weather. Estimates of annual soil loss using the Universal Soil Loss Equation and the Wind Erosion Equation represent estimates of first moments, or means of probability distributions. Actual soil loss can therefore vary about this mean. Given this probabilistic nature of annual soil loss, conserva-

tion plans developed to reduce mean annual soil loss could exceed the tolerance level. Hence, the spirit and intent of the Provision would be better served by conservation plans that assure annual soil loss to not exceed tolerance levels with an acceptably high probability. Stated another way, the conservation plans should assure that annual soil loss will not exceed tolerance levels an acceptability high percentage of the time.

A farm planning method has been suggested by Segarra, Kramer, and Taylor (SKT) that accounts for the probabilistic nature of annual soil loss. SKT formulate a chance-constraint in their linear programming (LP) model, following Charnes and Cooper. In their model, the total farm soil loss constraint is satisfied with a predetermined acceptably high probability. An advantage of their approach is its adaptability to conventional linear programming models, which are widely understood and easier to construct than other mathematical programming models. A potential limitation of the chance-constraint as implemented by SKT, however, is the linearization of a nonlinear relationship within the chance-constraint, which biases the total net returns downward.

The purpose of this study is to examine farm planning models that allow for the probabilistic nature of annual soil loss. More specifically, a representative southeastern Virginia crop farm is modeled. Solutions to the representative farm are obtained using the SKT approach as well as a straightforward nonlinear optimization procedure, and the results compared. Data and computational requirements are discussed.

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¹ The Provision defines highly erodible land as any soil having an erodibility index greater than or equal to 8. The erodibility index measures the inherent erodibility of the soil. All land capability class III-VIII soils are expected to qualify, as well as many class II soils.

² These include commodity price supports, disaster payments, crop insurance, Farmers Home Administration loans and loan guarantees, farm storage facility loans, Commodity Credit Corporation storage payments, and Conservation Reserve Program annual payments.

Theoretical Model

A chance-constrained formulation is used to account for the stochastic nature of the soil loss technical coefficients. Using Paris and Easter's terminology, the problem can be stated in primal form as:

$$\begin{aligned} (1A) \quad & \text{Max } E(p)'x, \\ (2B) \quad & \text{s.t. } PR(A_i'x \leq b_i) \geq \alpha_i, \\ & x \geq 0, \end{aligned}$$

where $E(p)$ is an $n \times 1$ mean column vector of expected net unit activity returns, x is a $n \times 1$ column vector of unit activity levels; A_i is the i^{th} row of stochastic technical coefficients of production relative to the nonrandom i^{th} input availability, b_i ; PR denotes probability; and α_i is the minimum probability by which the i^{th} constraint must be satisfied. The stochastic technical coefficient vector, A_i , is assumed to be distributed with mean $E(A_i)$ and variance Ω_i .

By standardizing the arguments of (1B), problem (1A) – (1B) can be restated as the primal form

$$\begin{aligned} (2A) \quad & \text{Max } E(p)'x, \\ (2B) \quad & \text{s.t. } E(A_i)'x + \theta(\alpha_i) (x'\Omega_i x)^{1/2} \leq b_i, \\ & x \geq 0, \end{aligned}$$

where $\theta(\alpha_i)$ represents the point on the corresponding density function where the i^{th} constraint, (2B), will be satisfied with a probability of at least α_i (Paris and Easter, P. 121). Since $\theta(\alpha_i)$ is positive for a non-risk preferring producer, the effect of the stochastic nature of the coefficients is to require more input use per unit of activity. In the context of this study, the stochastic nature of annual soil loss implies more soil loss per acre than would be implied by using the mean annual soil loss alone. The technical coefficients were assumed to be distributed $A_i \sim N(E(A_i), \Omega_i)$, although this assumption can be relaxed.

In this formulation, the adjustment to the mean annual soil loss depends on the choice of α_i . Presumably the government agency helping a farmer design a conservation plan would set α_i high. Different values of α_i can be expected to generate different optimal solutions, *ceteris paribus*. The value of α_i would presumably reflect how serious the government agency is about its mandate to control soil loss. Given the intent of the Provision, a likely value for α_i might be 0.95 or higher.³

To this point, the nonlinear optimization approach and the approach of SKT are identical. To implement their approach, SKT had to derive an acceptable linear approximation of the i^{th} constraint (SKT, p. 148–149). The nonlinear optimization does not require this linearization. Conceptually, the SKT approach treated the individual technical coefficients as the sum $[E(A_i) + \theta(\alpha_i)(\Omega_i^{1/2})]$. In other words, they replaced mean annual soil loss with the sum of the mean and some multiple of the standard deviation of soil loss, depending on the choice of α_i .

A solution to problem (2A) – (2B), however, can be obtained in a straightforward fashion using nonlinear optimization codes such as MINOS. MINOS uses a projected augmented Lagrangian algorithm, based on a method by Robinson, to solve the problem directly (Murtaugh and Saunders). While more costly to solve than the typical chance-constrained formulation, the straightforward nonlinear method does not require approximations that could have substantial influence over the optimal solution.

Study Area and Representative Farm Model

The study area is the Nansemond River and Chuckatuck Creek watersheds of the County of Isle of Wight and the City of Suffolk, situated contiguously in southwestern Virginia. These streams drain into the James River near its junction with the Chesapeake Bay, itself the recipient of recent attention concerning the levels of nonpoint source pollution found in its waters. The topography ranges from generally flat to gently rolling with steep slopes along streams. Soils of all capability classes are found in the study area, but most soils are in classes II through VIII. The soils vary widely in their susceptibility to erosion, but where erosion does occur, wind is likely to be as much of a factor as rainfall (U.S. Department of Agriculture). These watersheds were chosen for a Rural Clean Water Program because of their nonpoint source pollution problems.

The representative farm model employed in this

ipated possible political backlash generated by enforcement of the Provision. The comparison of methods in this study required the choice of a plausible value for α_i . Given that the Government is spending millions of dollars to achieve the goals of the Provision, the Government would most likely prefer α_i to ensure a reasonable probability of obtaining farm level soil loss targets. Choosing $\alpha_i = 0.9$ would imply a willingness to tolerate one chance out of ten that farm level soil loss goals would not be obtained, a risk that seems to this researcher too high for the Government to take. Choosing $\alpha_i = 0.99$ would most likely generate unacceptably large negative impacts on farm income. It seems plausible that the choice of α_i would lie between 0.90 and 0.99; hence the choice of $\alpha_i = 0.95$.

³ The author can offer no guidelines on how the Government might choose α_i . Obviously, the larger the initial value of b_i , the less impact a given α_i can have on restricting the constraint set to the point of infeasibility. Additionally, α_i cannot be chosen independently of antic-

analysis is a modified version of that described in McSweeney and Kramer. The production practices and constraints considered typical of crop farms in the study area. The model contains 99 activities and 43 constraints. The term net unit activity returns, or simply net returns, refers to the objective function value of a unit activity. For strictly cost incurring activities, the net returns are actually variable production costs, while for strictly revenue generating activities, the net unit activity returns are actually gross returns.

Each sell activity in the farm model reflects the sale of output from one acre of a given commodity under a particular government program participation scenario. The representative farm model includes four crops: corn, soybeans, wheat, and peanuts, which together accounted for over 90% of the harvested acreage in the study area in 1981 (U.S. Department of Commerce). Commodity support program participation only, crop insurance participation only, both crop insurance and support program participation, and nonparticipation scenarios are considered. The sale of each commodity is permitted under each of the program scenarios with the exception of peanuts for which support program participation was mandatory at the time of this analysis. The 14 sell activities are necessary to capture the farmer's different income perceptions associated with various participation possibilities held by the farmer. These were included because violation of the Provision will deny access to the support programs and federal crop insurance. The remaining activities in the farm model consist of production and resource acquisition activities. Conventional tillage as well as no-till cultivation are permitted for all crops except peanuts, for which no-till is not practiced in the study area. Conventional tillage is allowed with or without an overwinter cover crop for corn, soybeans, and peanuts. The cover crop is not allowed to be harvested. Wheat is allowed only as a double crop with late season soybeans.

Since Agricultural Stabilization and Conservation Service (ASCS) cost shares are part of current policy for controlling soil loss under the Agricultural Conservation Program (ACP), they are incorporated in the objective function values of the various eligible conservation activities as reductions in production costs. One-half of the costs for seed and seeding of a cover crop is eligible for this subsidy. A \$15 per acre subsidy for the adoption of no-till cultivation is also provided by RCWP funds. The representative farm can receive up to \$3,500 in cost-share funds.

The representative farm model consists of 252 acres of cropland, the average size farm in the study

area (U.S. Department of Commerce). All of the cropland is assumed to be subject to the Provision. Since soil loss can be reduced by removing land from production, the model includes an idle acreage activity. Idle acreage, however, must be protected by a cover crop, and has associated soil loss.

The soil loss coefficients and their variances were determined with the following procedure. A random sample of 10 farms was selected from ASCS county records. Each farm was divided into parcels, where parcel refers to a part of a field with the same cover and soil type. Soil loss was then calculated for each parcel using the Universal Soil Loss Equation (USLE). The mean USLE value for all parcels with a particular cover was used as the soil loss coefficient in the model, and the variance of these USLE calculations was used in the chance-constraint. The soil loss estimates were recalculated for all parcels, assuming that various soil loss control practices were implemented on the parcel. In the recalculation, the soil loss control practice was assumed to be implemented only if the parcel met design criteria. The mean recalculated USLE value for all parcels with a particular cover and soil loss control practice, as well as the variance, were then determined.⁴

Total annual farm soil loss was limited to 1103.145 tons, determined with the use of tolerance levels for each soil in the study area. These tolerance levels were weighted by the percentage of the total acreage in the City of Suffolk comprised by each soil (USDA, 1981). The resultant weighted-average tolerance level was 4.395 tons per acre, which was multiplied by the number of tillable acres to determine the soil loss limit.

Results of the Analysis

The representative farm model was first solved as a standard linear programming model. Most farm-level studies of soil loss control are of this type. The results appear in Table 1. The optimal solution contains 61.5 acres of support program conventional tillage corn, 40 acres of support program no-till corn, 53.5 acres of support program no-till wheat-beans, and 41.5 acres of conventional tillage peanuts. The remaining acreage is used to satisfy set-aside requirements of the support program corn and wheat. The optimal farm plan borrows over \$25,000. Total net returns are \$36,679.57, of which \$17,352.46 are from support program payments

⁴ The soil loss coefficients and variances, as well as a more detailed description of their determination can be found in Stavros.

Table 1. Farm Plan Solutions

| Activities | Standard LP Solution | Segarra, Kramer and Taylor Method | Nonlinear Optimization |
|--|-------------------------|--------------------------------------|---------------------------|
| Support Program No-till Corn | 40.03 Ac. | 74.66 Ac. | 45.20 Ac. |
| Support Program Conventional Tillage corn, no additional soil loss control practices | 60.48 Ac. | 25.85 Ac. | 24.04 Ac. |
| Support Program Conventional tillage corn with sod-filter strips | | | 30.50 Ac. |
| Support Program Conventional tillage corn with cover crop | | | 5.23 Ac. |
| Support Program No-till Wheat-Beans | 53.55 Ac. | 53.55 Ac. | 49.19 Ac. |
| Support Program Conventional tillage Peanuts, no additional soil loss control practices | 41.45 Ac. | 41.45 Ac. | 29.67 Ac. |
| Support Program Conventional tillage Peanuts with a cover crop | | | 11.78 Ac. |
| Corn Set aside | 35.18 Ac. | 35.18 Ac. | 38.66 Ac. |
| Wheat Set aside | 20.31 Ac. | 20.31 Ac. | 18.66 Ac. |
| Total Anticipated Annual Soil Loss | 1103.15 tons | 859.17 tons | 879.62 tons |
| Weighted std dev. of total annual soil loss | 0.0 | 243.98 tons | 223.53 tons |
| Total Required Credit | \$25,539.36 | \$26,288.67 | \$25,719.37 |
| Total Required Cost-Share Payments | \$ 612.95 | \$ 839.75 | \$ 832.71 |
| Total Support Program Payments | \$17,352.46 | \$17,352.46 | \$17,419.73 |
| Total Farm Net Returns | \$36,679.57 | \$35,840.35 | \$36,090.95 |

and \$612.95 are cost-share payments. Total anticipated soil loss is 1103.145 tons, the limit imposed on the farm.

The representative farm model was next solved following the procedures of SKT for $\alpha_i = 0.95$, and the results are presented in Table 1. Almost 26 acres of support program conventional tillage corn and almost 75 acres of support program no-till corn enter the optimal farm plan. The remaining acreage is as in the LP solution. Net returns are \$839.22 less than in the LP solution due strictly to the costs associated with the chance-constraint induced adjustment in the corn acreage. Farm borrowing is up slightly. Total anticipated soil loss is 859.17 tons, leaving a cushion of almost 244 tons of soil loss to ensure that the farm soil loss limit will be met 95% of the time.

The representative model was next solved directly using MINOS, and the results appear in Table 1. The acreage mix suggested by this optimal farm plan differs substantially from both the LP and SKT solutions. Almost 60 acres of support program conventional tillage corn enter the solution, but of this total, 31.5 acres are protected by sodfilter strips, and over 5 acres are protected by an over-winter cover crop. Slightly more than 45 acres of support program no-till corn also enter the optimal farm plan. The acreage of support program no-till wheat beans is slightly less than in either the LP or SKT solutions. Corn set-aside acreage is up slightly while wheat set-aside acreage is down slightly. Almost 12 acres of peanuts are protected by an over-winter cover crop. Total net returns suggested by this plan are less than in the LP solution, but more than obtained in the SKT solution. Support payments are up slightly, as in borrowing. Total anticipated soil loss is 879.62 tons, 20 tons more than the SKT solution. Conceptually, however, the 223.53 ton soil loss cushion in this solution provides the same probability that the soil loss limit will not be exceeded as the SKT solution.

Discussion

For the representative farm model used in this analysis, the nonlinear optimization appears to provide a more "acceptable" solution. Acceptable in the sense that more net returns are available to the farmer, while the farm plan has the same probability that the soil loss limit will be satisfied. SKT acknowledge that the process of linearizing the stochastic constraint results in the use of a biased estimate of the variance of soil loss (p. 149). Furthermore, the direction of the bias is such that the

adjustment to the soil loss coefficients results in larger technical coefficients than if an unbiased estimate of the variance were used. The effect of the bias is to exaggerate the magnitude of the annual soil loss coefficients. This in effect makes the constraint set more restrictive. The more restrictive constraint set can be expected to generate less total farm net returns than a set using an unbiased estimate of a variance, a result borne out by Table 1. SKT characterize their constraint as an acceptable approximation because the direction of the bias does not allow for a less restrictive constraint set (p. 149). While this is conceptually acceptable, a farmer might object to the greater income penalty.

Several aspects of the analysis warrant further attention. This particular representative farm tableau abstracts away from many of the concerns Soil Conservation Service personnel would likely face if this procedure were used to develop a conservation plan for a real farm. The nonlinear optimization as illustrated in this analysis is single period and static. A conservation plan, which is designed to control erosion for several years, would be determined with information concerning only the current time period. Also, the nonlinear optimization assumes that the conservation plan would be fully implemented at the end of the current time period with no allowance for adjustment in subsequent time periods, even though most conservation plans have a multi-year implementation period. However, a generalization of this model into a multi-period model would overcome this limitation.

Additionally, most conservation plans are constructed on a field-by-field basis, of critical importance when structural devices such as sodfilter strips, grassed waterways, or diversion structures are contemplated. In the model used in this analysis, the farm is tacitly assumed to be one large homogeneous field, and the farmer is free to allocate activities across the land so long as the soil loss constraint is not violated. The model, however, could be generalized to also allow field specificity. These shortcomings do not destroy the applicability of the method. Correcting them only adds to the richness of detail to the farm tableau. Such detail was omitted in this study for the sake of illustration.⁵

⁵ An attempt was made to simulate a field-by-field conservation plan by restricting the model such that only activities that did not exceed tolerance levels on a per-acre basis entered the optimal solution. Given that this particular tableau required 41.45 acres of peanut production to meet a marketing quota, and limited soybean acreage due to a nematode problem in the study area, the further restriction on per acre soil loss overly constrained the model resulting in an infeasibility.

Finally, the nonlinear optimization required a great deal more programming time and computer time. Given that the optimal plan obtained with the SKT approach penalizes the farmer less than 1% in terms of net returns relative to the nonlinear optimization solution, the SKT approach may be preferred.

Summary and Conclusions

The purpose of this study was to examine farm planning models that allow for the probabilistic nature of annual soil loss. More specifically, a representative southeastern Virginia crop farm was modeled. Solutions to the representative farm were obtained using both the Segarra, Kramer, and Taylor approach and a straightforward nonlinear optimization procedure, and the results compared. The results substantiate the conceptual limitations of the SKT approach. Relative differences between solutions obtained by the two procedures, however, suggest that the SKT approach may not present much of a disadvantage, especially if the increased time and resources required for the nonlinear optimization are accounted for.

The results of this analysis do suggest, however, that conservation plans can be designed that account for the probabilistic nature of annual soil loss, which at the same time impose slight income penalties on the farmer.

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