Optimal Rate of Applied Nitrogen and Choice of Reduced Tillage System

By

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Abstract: The objective was to compare optimal long-term farm level investments in conservation tillage systems and annual nitrogen use in wheat production from a private and social perspective. The performance of four tillage systems was simulated on a 243 hectare (600-acre) Oklahoma wheat farm with six soil types. A decomposition method was used to find the optimal tillage system. It was found that private producers would select a disk chisel system while the less erosive sweep system was optimal from a social perspective.

Introduction: Soil erosion constitutes a major problem facing farmers in Oklahoma. More than seven million acres are classified by the USDA as highly erodible. Yet many incentives for compliance with soil conservation practices within the framework of the federal commodity program will be removed in the future. The majority of compliance plans for wheat production land include the use of conservation tillage systems designed to retain plant residue on the soil surface throughout the year. Studies by Epplin et al (1994), Aw Hassan (1992), and Klemme (1983) have compared the profitability of conservation tillage systems. However, these studies have not fully considered the interaction between nutrient management, tillage system choice, and externality costs at the farm level.

The objective of this research is to compare the optimal social and private use of conservation techniques and commercial fertilizer to sustain productivity of soils in Garfield County, Oklahoma subject to limitations of offsite damages from soil erosion and fertilizer losses.

Problem and Model: The main objective of the study is to determine the most profitable long-term use of tillage systems and inorganic nitrogen when there is a concern about off-site damages from soil erosion and nitrogen loss. A representative 243 hectare (600 acre) wheat farm with six soil types was defined. The tillage types (in order of decreasing erosion and increasing herbicide use) to be considered were the plow (PL), disk-chisel (DC), sweep twice (S2), and sweep once (S1) systems. Non-zero externality charges are used in the social analysis. Assume a total horizon of 100 years (T) and that during this 100 year period the tillage machinery is replaced every 10 (mt) years. Therefore, the problem is to choose a tillage system every mt years and choose the wheat area and nitrogen use on wheat each year t on soil i to maximize the Net Present Value (NPV) over a T year period.

$$\underset{N,M}{\mathrm{Max}}\, NPV = \sum_{t=1}^{T}\sum_{j=1}^{T}\sum_{i=1}^{T} \left\{ \begin{array}{l} Aw_{jt}\left[P_w Y_{ijt}\left(D_{jt}, N_{jt}, TN03_{jt}, M_{mt}\right) - VC_t\left(N_{jt}, M_{mt}\right)\right. \\ \left. - t_n\, Nloss_{jt} - t_e E_{ijt}\right] + AP_{jt}\left[R_{pt} - t_n\, Nloss_{pt} - t_e E_{pt}\right] \end{array} \right\} \Big/ \left(1+r\right)^t$$

$$- \sum_{mt=1}^{T} M_{mt,i}\, TC_i \Big/ \left(1+r\right)^{mt} \qquad (1)$$

Subject to:

$$D_{jt+1} = D_{jt} - E_{ijt}(D_{jt}, M_{it}) \qquad (2)$$

$$D_{j0} = \bar{D}_{j0} \qquad (3)$$

$$\sum_{i=1}^{I} M_{it} = 1 \qquad \textit{for all } t \qquad (4)$$

$$Nloss_{jt} = f(D_{jt}, N_{jt}, TNO3_{jt}) \qquad (5)$$

$$TNO3_{jt+1} = g(D_{jt}, N_{jt}, TNO3_{jt}) \qquad (6)$$

$$TNO3_{j0} = \overline{TNO3}_{j0} \qquad (7)$$

$$A_{jt} = A_{jwt} + A_{jpt} \tag{8}$$

$$D, M, N, TNO3 > 0$$

where

t =1,2,…,T	represents the annual planning horizon
mt = 1,11,21,…T	is the machinery or tillage investment planning horizon
i= 1,2,…,I	is the number of alternative tillage systems
j =1,2,…,J	is the number of soil types on the farm
Y_{ijt}	is the yield of wheat in soil type j, using tillage i at time t, in metric ton per hectare
P_w	is the price of wheat in dollars per metric ton
R_p	is rental rate per one hectare of pasture
A_{jwt}	is the hectares of wheat on soil type j in year t
A_{jpt}	is the area of pasture on soil type j in year t
D_{jt}	is the depth of soil j at time t in meters
VC_t	is the variable cost at time t in dollars per hectare
TC_i	is the Present Cost of Tillage System i at the time of replacement.
N_{jt}	is the amount of nitrogen applied to wheat on soil type j at time t in kilograms per hectare
M_{itm}	is a zero-one integer variable of the type i of tillage used in time t
t_n	is the off-site cost in dollars per kg of nitrogen loss
$Nloss_{jt}$	is the amount of nitrogen loss in soil type j at time t in kilograms per hectare
t_e	is the cost in dollars per metric ton of soil lost
E_{ijt}	is the amount of eroded in depth in meters from soil type j when tillage system i is used at time t
S_{jt}	is the index for soil type j in the farm at time t
r	is the discount rate

The objective function equation (1) is the present value of net returns per hectare above the cost of nitrogen, machinery, and off-site damages aggregated across all tillage systems and soil type of the farm for the entire planning period. The constraints are given by equation (2) through equation (8). Equation (2) is a soil depth transition equation for soil type S_j. Equation (3) sets the initial soil depth at a given level. Equation (4) ensures that no more than one tillage system is chosen for a given year. Equation (5) allows determining the amount of nitrogen lost each year per soil type from surface runoff and leaching below the soil surface. Equation (6) determines nitrogen carryover.

Methods: The proposed model is of the discrete non-linear form. The size and complexity of the problem increases with the length of the planning horizon and the number of non-linear constraints. We were unable to obtain an optimal solution with the GAMS-MINOS software. However a decomposition method which used a spreadsheet solver was successful.

The study area was Garfield County, Oklahoma. Farming is assumed to take place in the Renfrow-Vernon-Kirland association, which contains six soil types: Kirland 53%, Vernon 21%, Renfrow 19%. Norge, Miller, and Zane soils account for 7% of the area.

Data required for estimating the functions for crop yield, soil nitrogen, soil erosion, and nitrogen loss for each tillage system were obtained by using the Erosion Productivity Impact Calculator (EPIC) (William et al., 1983). Simulation runs for this study were made over a 100 year-period with four level runs of applied nitrogen application (16, 50, 100, and 150 kg per hectare) in combination with each of the four tillage systems and six soil types. Thus, 1600 observations were generated.

The Oklahoma State University Enterprise Budget generator was used to estimate a budget for each of the four tillage systems. Variable costs include the costs of wheat seed, phosphorus, harvesting, pesticide, annual operating capital, machinery labor, fuel and repairs. Machinery ownership costs are the sum of depreciation, interest, and taxes. The budget summaries are shown in Table 1. The study assumes a base line wheat price of $110 per metric ton, while the price of nitrogen is $0.55 per kilogram.

Table 1. Annual and Net Purchase Cost for Alternative Wheat Tillage Systems for the Representative Farm

Type of Cost	Disk Chisel	Plow	Sweep Twice	Sweep Once
Operating Costs[a] ($/ha)	$138.20	$142.58	$174.34	$197.27
Fixed Costs ($)[b]	$84,864	$157,346	$67,231	$67,231

[a] Source: OSU Enterprise Budget

[b] Total cost to buy one machinery complement every 10 years less discounted salvage value for the 243 hectare farm.

The statistical estimation was made by considering each treatment or level of fertilizer application over a 100 year-period as one of 96 cross sectional units (4 fertilizer levels X 4 tillage systems X 6 soil types). Data from the four treatments for each soil type were pooled and arranged so that all observations appear together by tillage system within soil type. It is assumed that tillage system and treatment (applied nitrogen) have fixed effects. There are 100 replications corresponding to 100 years of simulation with a random effect assumed to be distributed as $N(0, \sigma_\delta^2)$.

The statistical model for each soil type can be represented as:

$$Y_{ikt} = \mu + \alpha_i + \beta_k + \delta_t + \varepsilon_{ikt}$$
$$i = 1.,\ldots,4, \quad k = 1.,\ldots,4, \quad t = 1,\ldots,100$$

where

Y_{ikt} is the observation when tillage system i is used and k'_{th} level of nitrogen applied at time t.

μ is the overall population mean

α_i the tillage effect

β_k is the treatment level effect

δ_t is the year effect assumed to be iid N(0, σ_δ^2)

ε_{ikt} is the experimental error associated with Y_{ikt}, assumed to be iid N(0, σ_ε^2)

A modified version of the Mitscherlich-Spillman (M-S) function (Taylor 1982, Young et al. 1985) was used for the yield response function. The estimated yield function was expressed as:

$$Y_t = Y_m - \alpha * EXP(\beta_1 / D_t + \beta_2 / N_t + \beta_3 / TNO3_t) + \varepsilon_t$$

Where

Y_t is the yield in metric tons per hectare

Y_m is the maximum attainable yield

$1/D_t$ is the inverse of topsoil depth at time t (m)

$1/N_t$ is the inverse of applied nitrogen at time t (kg/ha)

$1/TNO3_t$ is the inverse of residual nitrogen in soil at time t

α, β_1, β_2, β_3 are parameters

All models were estimated using the SAS PROC MIXED procedure. The data to estimate the offsite damage costs in the study area are not available. Based on estimation by Rebaudo and associates (1990), the study assumed an offsite damage cost of $1.5/mt. An 8% discount rate was also assumed following Aw Hassan (1992).

The problem was too large to solve with GAMS MINOS software. The empirical model specified above has more than 2400 linear and non-linear equations and 3620 variables. A branching method, which used the EXCEL solver software, was developed. The method (outlined in Figure 1) consists of decomposing the optimization problem into a large number of smaller optimization problems. The branching method is

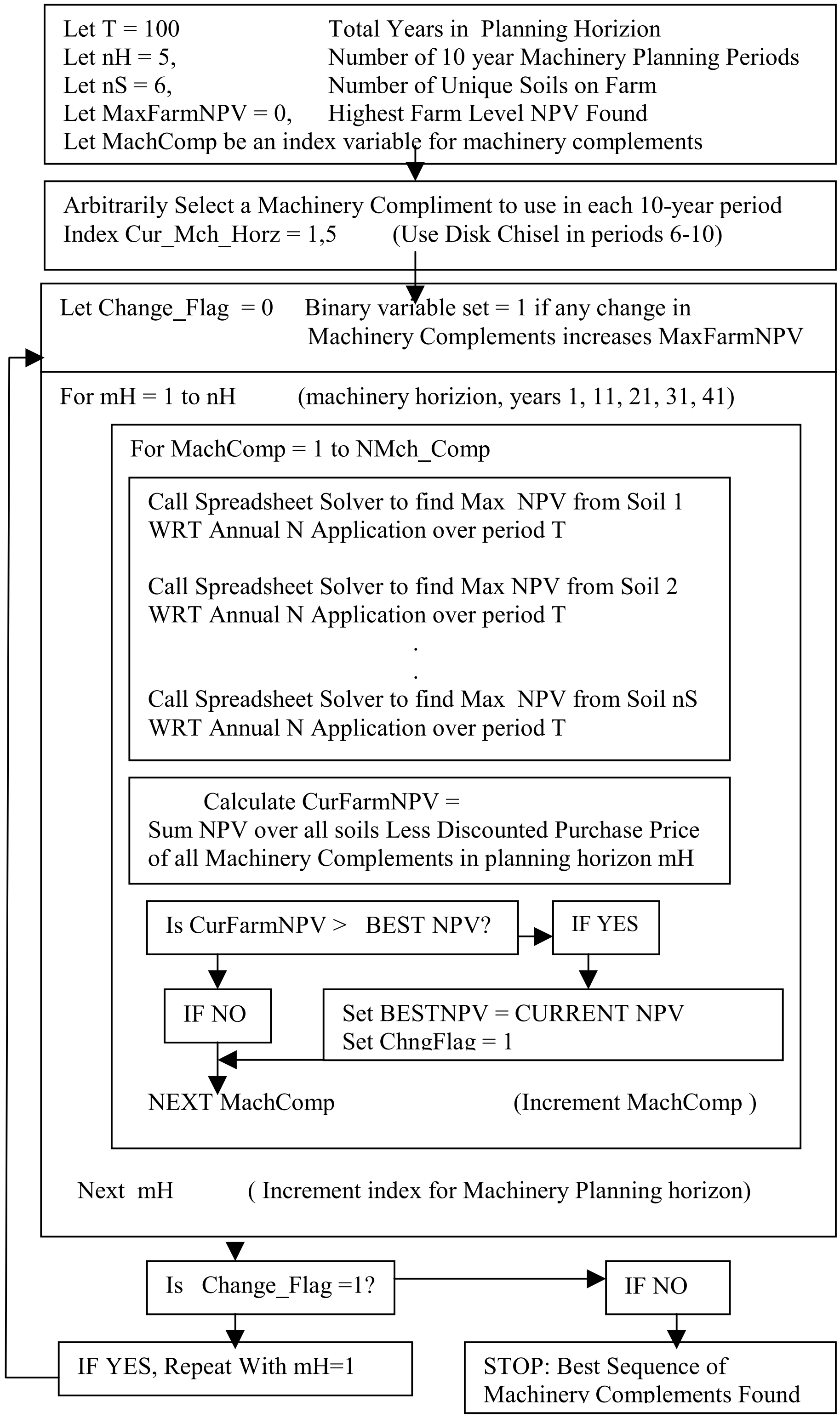

Figure 1. Outline of the Spreadsheet Algorithum.

similar to the methods of successive approximation algorithums in dynamic programming reviewed by Yakowitz (1982). First a tillage system was chosen for use in each of the 10-year machinery planning periods which begin in years 1, 11, 21, 31, and 41. (Use of the DC system was specified for the last 50 years). Equations (1) through (8) with their recursive linkages are entered into a separate spreadsheet page to represent a 100 year period for each soil. The solver was then called to determine the optimal annual level of nitrogen for wheat on each soil. The annual choice between allocating that soil to wheat or pasture was then made. The farm level NPV from the initial sequence of tillage systems was calculated.

Then, in year 1, each of the alternative tillage systems was examined to see if their selection at that time would increase the NPV. The tillage system adopted in year 1 that gave the highest NPV was chosen. Each of the alternative tillage systems was then tested to see if its selection in year 11 would increase the NPV. (Unfortunately, each time a different tillage system is considered, the solver must be called to re-optimize nitrogen applications and crop choice on each soil).

The examination of alternative tillage systems was then examined for years 21, 31, and 41. If none of the alternative tillage systems increased the NPV during any of the machinery planning periods then the problem was terminated. If an increase in the NPV was observed during any of the 5 machinery periods, then the process was repeated. The optimization process required from two to three hours on a 500 MHz microcomputer. The advantage is that for decomposable problems, solutions can be obtained by microcomputers and spreadsheet software which are generally available.

Results: The results of the estimation showed that all coefficients have the expected sign and that most were significantly different from zero at the 5 percent level. In general, the estimated equations fit the data well though the yield and nitrogen loss predictions were over estimated for some soils. The estimated functions for Kirkland soil type are shown on Table 2.

Data collected from variety trails on farmer fields in North Central Oklahoma, were used to adjust EPIC yields to reflect the actual yield of wheat on soil types in the study area. During the 100 year simulation period, average estimated yields with 100 kg of nitrogen applied per hectare varied from 3.03 MT/ha to 3.11 MT/ha for the S1 and S2 systems and from 3.09 MT/ha to 2.09 MT/ha for plow system. Figure 2 below shows yield changes in relation to soil depth by soil type.

Table 2. Functions for Wheat Yield, Residual Nitrogen, and Erosion for the Kirkland Soil Derived from EPIC Simulation Data.

Functions	Intercept[a]	D	N	TNO3	DC	PL	SW1
Erosion (m)	7.6521 (3.18)[c]	-3.6315 (-3.06)			1.4395 (9.48)	9.5861 (16.27)	-0.0372 (-2.66)
Yield[b] MT/ha)	0.4761 (8.01)	0.3350 (3.37)	20.1668 (11.41)	10.1141 (12.00)			
Nitrogen Carryover (kg/ha)	-48.4702 (-8.27)	22.3470 (7.71)	0.2852 (12.37)	0.7589 (44.98)			
Nitrogen Loss (kg/ha)	-8.6885 (-5.52)	46.9016 (6.07)	0.0209 (4.16)		29.7562 (26.79)	105.4920 (32.10)	-86.8852 (-5.55)

[a] For dummy variable tillage intercept represents SW2
[b] For yield variables are inverse of variable shown on Table
[c] Numbers in parenthesis are t-values.

The study found that the optimum levels of applied nitrogen were slightly lower for the sweep systems, (varying from 117 kg/ha to 132 kg/ha, depending on the soil type) than for the disk chisel, (varying from 123 kg/ha to 135 kg /ha). At the farm level, as shown in Table 3, the optimum nitrogen application for the private case varied from 126 kg/ha to 134 kg/ha depending on the soil type. For the social optimization, nitrogen applications vary from 104 kg/ha to 130 kg/ha. When off-site damages were not taken into account, the net present value of the disk chisel was higher than the net present value of all the other systems on all soils, and the net present value of the S2 system was the lowest. The analysis shows that if externality charges were considered producers would adopt the less erosive sweep systems which would almost maintain current yields without increased nitrogen as indicated in Figure 3. In Figure 3 the nitrogen-soil depth isoquants for the farm with the DC system after 10 and 50 years are weighted averages of the individual soil isoquants. The optimal path shows nitrogen application would increase by about 3 kg per ha over the 40 year period. The socially optimal S2 system shows a nearly constant level of nitrogen and soil depth.

Figure 2. Yield Response to Soil Depth by Soil Type with 100 kg N/ha Applied N.