# Optimal distribution of conservation practices in the Upper Washita River basin, Oklahoma

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**Background:**

The Upper Washita River basin in southwestern Oklahoma has been the subject of extensive research since the 1930s and is also a participating watershed in the long-term USDA Conservation Effects Assessment Project (CEAP) effort. Much of the research has focused on developing and testing computer models and tools to simulate the impacts of agricultural management practices on soil and water resources. While a substantial portion of these research efforts have focused on the environmental impacts of management practices, economic considerations are now receiving greater attention since funding agencies are better appreciating the link between farm economics and producer adoption of the conservation practices. This paper contributes to a better understanding of how resource conservation benefits of limited available funds can be maximized by optimal distribution of the practices based on publicly available spatial distributions of the biophysical attributes of agricultural lands. We specifically determine optimal conservation practice distributions for two sub-basins of the Upper Washita River basin: the Fort Cobb Reservoir Experimental Watershed (FCREW) and the Little Washita River Experimental Watershed (LWREW).

Study Area and Data Sources:

The two subbasins lie in the southern and northwestern portions of the Upper Washita River basin (Figure 1). Winter wheat and beef cattle grazing are predominant enterprises in this area. Key data sources for the study included the USDA Cropland Data Layer (CDL), which provides cropland cover history at a resolution of 30-m, USDA-NRCS Soil Survey Geographic Database (SSURGO) – the most detailed soil survey data available, and USDA's PRISM database at a precision of $4km^2$, which provides detailed gridded weather data. Economic input and output price data were also obtained for the entire state from the Economic Research Service (USDA-ERS), National Agricultural Statistics Service (USDA-NASS) and the Agricultural Marketing Service (USDA-AMS).

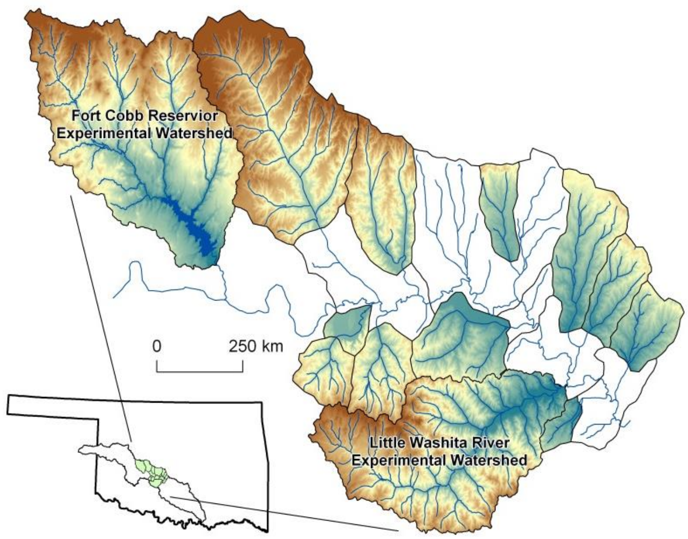


Figure 1. Locations of FCREW and LWREW sub-basins within the Upper Washita River basin.

**Methodology:**

Optimal conservation practice placement in the FCREW and LWREW subbasins were determined by employing the following three-step process.

Conservation practice simulation. Various (Monte Carlo) combinations of conservation practice implementations were simulated to determine the economic and environmental (soil and water) impacts associated with each practice distribution. This process was performed in order to evaluate the impacts of all plausible combinations of conservation practices applicable to the area.

Generation of metamodels. Metamodels are statistical response functions that capture the complex relationships between model input parameters and output. In particular, the metamodels developed in this study represent the functional relationships between practice placement configuration and each relevant economic or environmental indicator. Metamodels were developed for the following environmental indicators: edge of field and watershed loadings of sediment, runoff, total nitrogen, and total phosphorus. Metamodels were also developed for net farm returns, the key farm-level economic indicator.

Optimization using metamodels as input. In the final step of the optimization process, the metamodels are used in an optimization framework to determine the optimal conservation practice designation for each of the polygons. An optimization program was developed using the General Algebraic Modeling System (GAMS) modeling platform. Alternative optimization problems were solved to determine optimal practice distributions to obtain specific reductions in (1) sediment, (2) total nitrogen, and (3) total phosphorus loads to the outlet of each watershed given a funding constraint on conservation practice dollars. In addition, an additional optimization problem was solved to determine the least cost practice distribution given exogenous limits on all environmental indicators.

Computer simulation models:

The computer modeling system used for this study is a fully-linked suite of economic and biophysical models. Agricultural Policy Environmental eXtender (APEX; Williams et al., 2000) is a daily time step field-scale biophysical model that simulates crop growth, sediment losses, runoff, and nutrient fate and transport in response to weather, soil, and land use management data. Soil and Water Assessment Tool (SWAT) is a watershed router that takes APEX output as input and generates information on the transport and delivery of water, sediment, nutrients, and pollutants from source land uses to the outlet of the watershed of interest. Farm-level Economic Model (FEM; Osei et al., 2000) is a whole-farm annual time step economic simulator that is linked to APEX for transfer of biophysical and decision-variable data in order to ensure consistent simulation of all relevant scenarios. APEX, SWAT, and FEM were calibrated prior to use in the simulations.

The fully linked biophysical – economic modeling system was used to determine net farm returns for each simulation. The Agricultural Policy Environmental eXtender (APEX) model was used to simulate the agronomic and biophysical impacts on a daily time step. Crop yield data estimated by APEX was passed on to the Farm-level Economic Model (FEM) for each simulation to determine the corresponding values of the economic indicators. Both APEX and FEM have been calibrated extensively and used successfully in several watersheds in Oklahoma. For this study, APEX and FEM were further calibrated using recent data on crop yields, nutrient losses, custom rate surveys, and farm financial performance. The calibrated models were then used in the simulations.

APEX and FEM have been linked in a previous effort to enable seamless transfer of data between the two models (Osei et al., 2008). In this study the two models were applied in a dynamic linkage (Figure 1) to determine the environmental and economic impacts of each conservation practice scenario for each simulated land area. The two models were calibrated separately prior to their use in the simulations.

FEM is a whole-farm simulation model that is used to simulate farm-level economic impacts in response to alternative agricultural policy and practice scenarios. FEM operates on annual time step and can be executed for extended periods of 30 years or more. Key categories of input data required to simulate a farm in FEM include type of livestock system, manure management methods, cropping systems and cultural practices, facilities and equipment, field attributes, input and output prices, and other external factors. Economic outputs generated by FEM include total revenue, total cost, net farm returns, livestock rations, crop and livestock sales, costs of individual production components (crop and livestock enterprise costs, fertilizer expenses, labor costs, etc.), debt payment, and owner’s equity (Osei et al., 2000).

Prior to the simulations performed in this paper, FEM was calibrated against current (2013 and 2014) farm custom rates tabulated for many states in the continental U.S. Estimated costs of planting, tillage, nutrient, and chemical application operations and harvesting costs from the FEM model were all found to be consistent with corresponding custom rates data reported for recent years. A comparison of FEM output to selected custom rates data is shown in Table 1.

APEX is a modified version of the Erosion Productivity Impact Calculator (EPIC) model that has been used widely to simulate alternative management scenarios such as variations in manure and fertilizer application rates, tillage options, and adoption of other cultural and structural management practices. APEX operates on a daily time step and can be applied for a wide range of soil, landscape, climate, crop rotation, and management practice combinations. It can be executed for a single field or used for a wide range of multi-filed configurations including whole farms or small watersheds. APEX is detailed enough to simulate precise management practices such as filter strip impacts on nutrients losses from waste application fields. The main APEX components are weather, hydrology, soil temperature, erosion-sedimentation, nutrient cycling, tillage, management practices, crop management and growth, and pesticide and nutrient fate and transport. Choice of simulated cropping system, manure and/or fertilizer nutrient characteristics, tillage practices, soil layer properties, and other characteristics are input for each simulated subarea. Key outputs include crop yields, edge-of-field nutrient and sediment losses, and other water and nutrient balance indicators.

APEX was calibrated against annual county-level crop yield data assembled by the USDA National Agricultural Statistics Service (USDA-NASS) and available on the USDA-NASS web site. The model is included in the Nutrient Tracking Tool (NTT; Saleh et al., 2011) and has been calibrated extensively by many other authors for use to assess edge-of-field water quality impacts across a wide variety of agricultural lands in the U.S. and other nations (Gassman et al., 2010).

Data Sources:

A number of data sources were used for this study. Many of the following datasets are incorporated into the web-based NTT tool. Others were assembled specifically for this study. As described below, various Geographic Information Systems (GIS) data layers were overlaid in order to determine the distribution of wheat growing areas in Caddo County, Oklahoma.

Cropland data layer (CDL): A four-year GIS history of cropland cover for the entire United States was obtained from the USDA-NRCS data server. The cropland data used for this study covered the time period of 2010 through 2014. The CDL data is available at a 30-meter level of precision. The data layer for the study area for 2014 includes tens of thousands of field polygons that reflect the distribution of wheat fields in the County. While these field boundaries do not represent the size of farmlands, they do represent approximate wheat field dimensions in 2014.

LiDAR (Elevation) Data: Digital elevation data from satellite imagery is available for the study area. The LiDAR data offers a 10 m resolution of relief data and was used for this study to obtain more precise slope information for the simulations. This information was used to obtain more refined estimates of slope for each of the crop-soil polygons. Due to the precision of the LiDAR imagery, multiple slope values were obtained for most crop-soil polygons, more accurately reflecting real topographical features.

SSURGO soils data: The USDA-NRCS SSURGO soils data for each survey area of the United States have also been assembled. For this study, the SSURGO data layer was overlaid on the CDL data in order to determine the soil types applicable to wheat production fields in Caddo County, Oklahoma. The overlay of SSURGO soils data on the CDL crop cover produced over 500,000 polygons or subareas representing field-soil type combinations where wheat is grown in Caddo County, Oklahoma. The overlay of the slope shape file on the crop-soil polygons resulted in almost 5.5million polygons. The high level of precision afforded by these polygons can help provide improved cost-effectiveness of conservation practice implementation. However, for this study, a lower level of slope precision was used due to the number of simulations required to capture the variations in slope. Furthermore, for the present study, the number of polygons was reduced by excluding polygons less than 0.01 acres in size.

Weather data: Precipitation, minimum and maximum temperature, solar radiation, and other key weather variables were obtained from the USDA Parameter-elevation Regressions on Independent Slopes Model (PRISM) database. The weather data are also available on the NTT server and were used for the present simulations. The PRISM data used for this study are available at a 4-kilometer resolution for the continental U.S. The simulations presented here were performed with a 47-year history of weather data from 1960 through 2006 to adequately reflect typical weather patterns in Caddo County, Oklahoma.

Wheat management: Typical winter wheat cultural practices for Caddo County, Oklahoma, were obtained from previous work in the area (Osei et al., 2012) and from the USDA NRCS crop management zones (CMZs) applicable to central Oklahoma. For simplicity of the present study, only one winter wheat management was used for all soils. A wheat management including spring tillage was chosen for the baseline simulations to represent the status quo. The specific list of field operations included in this management file is provided in Table 2. The wheat management file was converted into APEX and FEM formats for the model simulations. The same dates and field operations were used for all soils. The only parameter that varied in all simulations was the biophysical parameters of the soil; no management information was changed. In addition to the operations specified in Table 2, the APEX simulations included a "kill" operation that terminated the growth of the wheat crop one day after each year's harvest operation. FEM also included various post-harvest operations such as drying, handling, and marketing. Finally, it is important to note that the management information contains no irrigation. The present study was performed to reflect dryland wheat grain production in central Oklahoma.

Price and other economic data: The wheat price used for the simulations was the average of the most recent five years of annual average wheat price (2010 through 2014), obtained from the USDA Agricultural Prices Summary database. Fertilizer prices were also based upon the most recent five year average price. Equipment prices were based on current retail prices of the same types of field implement, tractors and combines. Labor wages, interest rates and other borrowing terms were also based on recent averages published by USDA and lending institutions. Finally, a 500-acre representative farm was used in all economic simulations to determine the farm economic implications of the conservation practice scenarios.

**Conservation Practice Scenarios**

Three conservation practices have received the most attention in the upper Washita River watershed area: no-till, conversion to grassland, and riparian buffer zones. Each of these practices was simulated and compared to the baseline management practice described above. A 47-year time horizon was used for each scenario in both APEX and FEM.

No-till: No-till was simulated by eliminating baseline tillage practices from simulations. All other farm management information were kept the same as the baseline.

Conversion to pasture: This conservation practice was simulated by assuming that all land uses on which winter wheat was simulated would now be simulated with Bermuda grass pasture. Bermuda grass was chosen because it is a predominant pasture grass species in central Oklahoma.

Riparian buffer: This conservation practice consists of a buffer zone developed at the downstream edge of fields that are adjacent to surface waters. To simulate this practice, a list was constructed of all polygons whose land use type is water, or are adjacent to polygons with that land use type. For each of these polygons, the APEX simulation was configured to force routing of runoff from the polygon through the riparian buffer subarea prior to leaving the area. This routing feature essentially reduces runoff volumes and concentration of sediment, nutrients, and other chemicals that would have been transported by the runoff water. Economic simulation of the riparian buffer entailed all cost implications including initial establishment and annual maintenance cost of the buffer zone, as well as the opportunity cost of foregone cropland or pasture area.

**Conservation Practice Optimization:**

Conservation practice optimization in the upper Washita River watershed was approached from two perspectives. The first is maximizing the environmental benefits subject to a given constraint on conservation investment dollars. The second is minimizing the cost of obtaining a target pollution reduction goal. Standard optimization methods afford us the opportunity of making the most cost-effective decisions in both situations.

<u>Environmental benefit maximization subject to funds constraints:</u> In determining how limited funds should best be allocated to mitigate environmental pollution concerns, suppose we have $n$ subbasins, indexed by $i = 1\ to\ n$. We also have $m$ practices, indexed by $j = 1\ to\ m$. Let $a_{ij}$ represent the number of units (typically acres) of practice $j$ in subbasin $i$. Then our goal is to find the best possible set of values of $a_{ij}$ for each subbasin $i$ and each practice $j$. What turns out to be the best possible distribution of practices also depends on the environmental indicators of interest. So we also have the indicators indexed by $k$. For instance, $k = 1$ for nitrogen, $k = 2$ for phosphorus, and $k = 3$ for sediment.

The benefit maximization problem is defined as follows:

$$Max\ B = \sum_i \sum_j a_{ij}\, b_{ij}$$

Subject to the following constraints:

$$C = \sum_i \sum_j c_{ij} a_{ij} \leq C^{Lim}$$

$$A_j \geq a_{ij} \geq R_{ij}$$

In the above equations, $B$ is the total environmental benefit, which can actually be a complex function of the practice distributions (the $a_{ij}s$), which is captured by the model simulations. However, in this application we linearized the complex relationships by developing linear metamodels that approximate the relationships between the conservation practice parameters and the environmental and economics outcomes. So $B$ is the summation of the benefits from each individual practice implementation, with the unit benefits represented by $b_{ij}$. Similarly, the total cost is represented by a linear summation across all the practice implementations (the values of the $a_{ij}s$) with the unit costs ($c_{ij}$) as the weights. The cost constraint limits us to a total dollar value of $C^{Lim}$.

Finally we also require that for each subbasin, the practice areas (the $a_{ij}s$) are no larger than the total subbasin area ($A_j$) and also that the practice areas are at least as large as conveniently chosen corresponding reference values $R_{ij}$. If we choose to optimize with reference to a no-BMP situation, then the reference values, $R_{ij}s$ would all be zero. However, if we optimize with reference to a current situation that already has some BMP implementation, then not all reference values would be zero. In that case the $R_{ij}$s would reflect the current BMP implementation areas.

The solution to the above optimization problem is the set of values for the $a_{ij}s$ that maximize the environmental benefit (nitrogen reduction, phosphorus reduction, sediment reduction, etc.) subject to the cost constraint and the other standard constraints as outlined above. A special Farm-level Economic Model (FEM) command line triggers a call to the optimization solver to solve the problem and return the solution values.

<u>Cost-minimization subject to a predetermined environmental benefit:</u> The cost minimization problem is similar to the benefit maximization alternative presented above. This optimization problem is defined as follows:

$$Min\ C = \sum_i \sum_j a_{ij}\, c_{ij}$$

Subject to the following constraints:

$$B = \sum_i \sum_j b_{ij} a_{ij} \geq B^{Lim}$$

$$A_j \geq a_{ij} \geq R_{ij}$$

The symbols are defined as in the previous case. The only difference here is that we are minimizing cost subject to a required benefit level, $B^{Lim}$.

The solution to the above optimization problem is the set of values for the $a_{ij}s$ that minimizes the cost of practice implementation subject to the required level environmental benefit (required nitrogen reduction, phosphorus reduction, sediment reduction, etc.) and the other standard constraints defined above.

**Results and Implications:**

Results of the optimizations indicate that substantial cost savings could be achieved if conservation practice distributions could be optimized. In general, a given reduction in sediment or total nitrogen loads is less costly to achieve than the same reduction in total phosphorus loads. However, while this is achievable in theory, practical implementation of conservation practice distributions would hinge on willingness of landowners to implement those specific practices on their fields.

No-till practices are shown to reduce nitrogen and sediment losses, but increase phosphorus losses and runoff volumes. With respect to farm economics, no-till winter wheat production in central Oklahoma is indicated to result in a small cost reduction while maintaining yields. Consequently, for nitrogen or sediment loss reduction, no-till appears to be a win-win option that can be implemented across most of the landscape. Summary statistics on per acre impacts of no-till on farm net incomes and environmental indicators are show in Table 3.

On the contrary, conversion to grassland cover entails a significant cost to farmers and would also yield substantial and consistent reductions in all environmental indicators (runoff volumes and sediment and nutrient losses). Similar results are also indicated for riparian forest buffer zones (not presented here). Thus, optimal conservation practice distribution across the study area entails widespread no-till adoption and targeted implementation of cropland conversion to grassland and riparian buffer zones.

TABLES:

| **Table 1. Comparison of custom rates and FEM model output ($/acre).** | | | |
|---|---|---|---|
| | | FEM Model Output | |
| *Field operation* | *Custom rate* | *Fixed Cost* | *Total* |
| Moldboard plow | 18.68 | 13.37 | 19.79 |
| Tandem Disk | 13.46 | 7.36 | 15.13 |
| Chisel Plow | 14.32 | 7.35 | 16.33 |
| Field Cultivator | 11.36 | 2.88 | 11.76 |
| Offset Disk | 14.4 | 5.96 | 16.23 |
| Rotary Hoe | 7.56 | 4.89 | 8.06 |
| Row Crop Cultivator | 10.42 | 4.99 | 11.68 |
| Bulk Fertilizer Spreader | 6.61 | 1.14 | 5.69 |

Table 2. Field operations simulated for winter wheat

| **Date** | **Operation** | **Application Type** |
|---|---|---|
| February 5 | Fertilizer / Nitrogen | Surface |
| February 5 | Fertilizer / Phosphorus | Surface |
| May 21 | Harvest wheat | |
| June 15 | Disk | - |
| July 15 | Moldboard plow | |
| August 15 | Disk | - |
| October 20 | Plant wheat (drill) | - |

Table 3. Summary statistics of impacts of conservation practices on selected indicators.

| | | | | |
|---|---|---|---|---|
| | Units | Minimum | Maximum | Mean |
| No-till | | | | |
| Total Nitrogen | Lb/ac reduction | -1.37 | 4.35 | 0.86 |
| Total Phosphorus | Lb/ac reduction | -3.40 | 0.11 | -0.21 |
| Sediment | t/ac reduction | 0.09 | 4.86 | 0.79 |
| Net income | $/ac reduction | -15.74 | -11.24 | 012.08 |
| Conversion to grassland | | | | |
| Total Nitrogen | Lb/ac | 6.01 | 34.27 | 11.67 |
| Total Phosphorus | Lb/ac | 0.13 | 3.21 | 0.65 |
| Sediment | t/ac | 0.16 | 7.63 | 1.30 |
| Net income | $/ac | -63.21 | 85.99 | 47.20 |

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