Environmental Management (2010) 45:1164–1174
DOI 10.1007/s00267-010-9458-6

Evaluating Conservation Program Success with Landsat and SWAT

Michael J. White · Daniel E. Storm · Philip Busteed · Scott Stoodley · Shannon J. Phillips

Received: 30 March 2009 / Accepted: 12 February 2010 / Published online: 7 March 2010

Abstract In the United States, many state and federally funded conservation programs are required to quantify the water quality benefits resulting from their efforts. The objective of this research was to evaluate the impact of conservation practices subsidized by the Oklahoma Conservation Commission on phosphorus and sediment loads to Lake Wister. Conservation practices designed to increase vegetative cover in grazed pastures were evaluated using Landsat imagery and the Soil and Water Assessment Tool (SWAT). Several vegetative indices were derived from Landsat imagery captured before and after the implementation of conservation practices. Collectively, these indicators provided an estimate of the change in vegetative soil cover attributable to conservation practices in treated fields. Field characteristics, management, and changes in vegetative cover were used in the SWAT model to simulate sediment and phosphorus losses before and after practice implementation. Overall, these conservation practices yielded a 1.9% improvement in vegetative cover and a predicted sediment load reduction of 3.5%. Changes in phosphorus load ranged from a 1.0% improvement to a 3.5% increase, depending upon initial vegetative conditions. The use of fertilizers containing phosphorus as a conservation practice in low-productivity pastures was predicted by SWAT to increase net phosphorus losses despite any improvement in vegetative cover. This combination of vegetative cover analysis and hydrologic simulation was a useful tool for evaluating the effects of conservation practices at the basin scale and may provide guidance for the selection of conservation measures subsidized in future conservation programs.

Keywords SWAT · Modeling · Watershed management · Nutrients · Nonpoint source pollution · Remote sensing

M. J. White (✉)
USDA-ARS Grassland, Soil, and Water Research Laboratory, 808 East Blackland Road, Temple, TX 76502-6712, USA
e-mail: mike.white@ars.usda.gov

D. E. Storm
Biosystems Engineering, 110 Ag Hall, Oklahoma State University, Stillwater, OK 74078-6021, USA

P. Busteed
USDA-ARS, Grazinglands Research Laboratory, 7207 West Cheyenne Street, El Reno, OK 73036, USA

S. Stoodley
V.P. Water Resources, ENTRIX Inc., 20 Trafalgar Square, Suite 416, Nashua, NH 03063, USA

S. J. Phillips
Water Quality Division, Oklahoma Conservation Commission, 4545 N. Lincoln Boulevard, Lincoln Plaza Office, Suite 11A, Oklahoma City, OK 73105, USA

In the United States of America (USA), state and federal agencies are under pressure to quantify the impact of the publically funded conservation programs they administer. Considerable resources are allocated to these programs in the USA. The Environmental Quality Incentives Program (EQIP), which is administered by the US Department of Agriculture (USDA) and provides assistance for landowners seeking to establish conservation practices, received $1.02 billion nationally in 2006 (Zinn and Canada 2007). The Clean Water Act, Section 319, program administered by the US Environmental Protection Agency (USEPA) distributed $204 million in federal funds (40% state match) to states for use in nonpoint source pollution reduction projects (USEPA 2007). Both the USEPA and the USDA have expressed significant interest in the effectiveness of these programs. The USDA initiated the Conservation Effects Assessment Project (CEAP) in 2003 in an effort to quantify the environmental benefits of USDA conservation programs (USNRCS 2009). The USEPA now requires measures of Section 319 progress success, including implementation milestones, reduction estimates for non-point source pollutant loads, and information on water quality improvements, the principle of which is delisting from a state's 303(d) list (Hardy and Koontz 2008).

The accurate evaluation of conservation programs is not an easy task. Water quality data are often collected before and after implementation of conservation practices to demonstrate improvements associated with these programs. To account for changes due to weather, water quality data are generally also collected in a control watershed in the same region that receives no conservation practices, significantly adding to the total monitoring cost. This paired watershed design (USEPA 1993) is a useful tool, but it is expensive and may be complicated by other factors that influence pollutant load in either the control or treatment watersheds. Changes in land use, point source contributions, and inherent pollutant storage within the system may mask the effect of conservation practices on pollutant loads. Despite these possible limitations, this approach provides a reasonable measure of conservation practice effectiveness and has been effectively used to document statistically significant improvements in relatively short periods of time (Oklahoma Conservation Commission 2008; Bishop and others 2005).

The use of measured efficiencies from conservation practices installed and monitored at other sites may also be used to evaluate conservation practice effectiveness. Tools such as the USEPA's Spreadsheet Tool for the Estimation of Pollutant Load (STEPL) (Tetratech 2005) utilize this approach. Unfortunately, these efficiencies are generally based on data collected at locations dissimilar to the site in question and contain a great deal of uncertainty. However, conservation practices are highly site specific (Djodjic and others 2002; Gitau and others 2004). Other tools, such as the BMP Effectiveness Assessment Tool (Gitau and others 2005), use a more comprehensive database of conservation practices and allow the user to specify soil hydrologic group and slope class to provide effectiveness estimates from the available literature that more closely match local conditions. This approach is appealing because it is simple, requires relatively little data and no water quality monitoring.

Models such as the Soil and Water Assessment Tool (SWAT) (Arnold and others 1998) have been accepted as surrogate measures to quantify the impact of conservation programs. Though more complicated than the previous approaches, hydrologic models have the potential to better account for local conditions. SWAT inputs, for example, include chemical and physical soil properties, weather, topographical characteristics, and management. SWAT is being used in the national CEAP efforts by the USDA (Gassman and others 2007) and as a field-scale conservation practice evaluation tool (White and others 2009a). Many other researchers have used SWAT to evaluate conservation practices in a variety of systems (Vache and others 2002; Chu and others 2005; Bracmort and others 2006).

The primary objective of this research was to quantify sediment and phosphorus load reductions attributable to conservation practices implemented at the basin scale.

In 2001, the Oklahoma Conservation Commission (OCC) received funding from the USEPA under Section 319(h) of the Clean Water Act to cost-share the implementation of conservation practices in the Lake Wister Basin. The OCC's program provided funds for local ranchers and poultry growers to implement conservation practices that focused on forage management and the improvement of poultry and cattle facilities. Conservation practices evaluated in this research focused on forage and grazing management: Bermuda grass (cynodon dactylon) sprigging, fescue (*Schedonorus phoenix*) seeding, liming, fertilizing, cross fencing, and limited grazing in riparian areas. These conservation practices were selected specifically to reduce phosphorus and sediment loads from grazed pastures to Lake Wister. A combination of remote sensing techniques and SWAT simulations was utilized in this research.

Materials and Methods

Study Area

The Lake Wister Basin covers approximately 2,400 km^2 in southeastern Oklahoma and southwest Arkansas, USA (Fig. 1). The OCC implemented conservation practices only in the Oklahoma portion of the basin, roughly two-thirds of the 260,000 ha basin. Only a small fraction of the basin (1.25%) received subsidized conservation practices. Water quality problems in Lake Wister and its primary tributary, the Poteau River, stem primarily from excessive sediment and nutrient loading. The Poteau River was listed on the USEPA 303(d) list as threatened or impaired by causes of metals, nutrients, siltation, organic enrichment/dissolved oxygen, taste and odor, suspended solids, and noxious aquatic plants. Lake Wister was listed for nutrients, siltation, flow alteration, taste and odor, and suspended solids, was hypereutrophic, and violated the state's turbidity standard for lakes (Oklahoma Water Resources Board 1996, 2003). Lake Wister was of particular interest because it is used as a water supply by several surrounding municipalities.

The Lake Wister Basin is primarily pasture and forest; poultry production and cow-calf ranching are the dominant

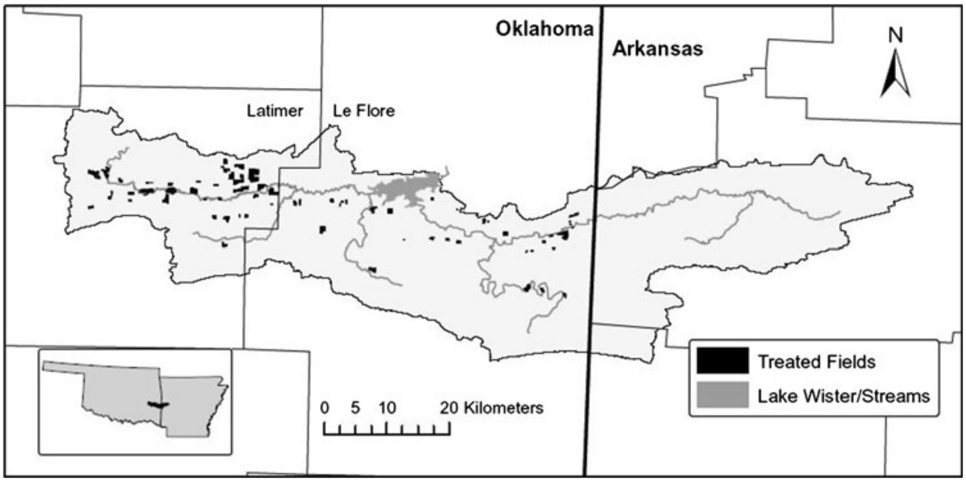

Fig. 1 Fields treated with forage or grazing management conservation practices as part of the Oklahoma Conservation Commission's Conservation Water Quality Program in the Lake Wister Basin

agricultural activities. The basin is divided nearly equally by the Arkansas Valley and the Ouachita Mountains eco-regions (Omernik 1987) and receives 1,300 mm/year precipitation on average. The average slope in the basin is 12% but varies significantly with land use, with higher slopes in forested areas. The Oklahoma portion of the basin contains 275 poultry houses. The manure and bedding material from poultry production (referred to as poultry litter) is utilized locally as fertilizer for permanent pastures; approximately 34,000 mg of poultry litter (480,000 kg of phosphorus) was produced in the Oklahoma portion of the basin annually (Storm and others 2006). The application of poultry litter greatly improved forage production for cattle consumption but significantly increases soluble phosphorus concentrations in surface runoff (Sauer and others 2000; Pierson and others 2001).

SWAT Model Description

SWAT is a basin-scale distributed hydrologic/water quality model used to evaluate streamflow and pollutant losses from mixed landuse basins. The model is the product of 30 years of model development by the USDA-Agricultural Research Service and appears in more than 250 peer-reviewed published articles (Gassman and others 2007). SWAT is a process based model which seeks to replicate hydrology, plant growth, land management, and nutrient and sediment transport process. The model can readily utilize soils, topography, and land-use data within a Geographic Information System (GIS) because it allows a basin to be simulated as a collection of discrete units, each with differing properties and parameters. SWAT operates on a daily time step and long-term simulations can be performed using simulated or observed weather data.

One of the primary strengths of the SWAT model is the representation of field management activities within the model. Individual management activities such as planting, irrigation, fertilization, grazing, harvesting, and tillage are simulated as discrete management operations scheduled by date. SWAT has been extensively used to evaluate the effects of management related conservation practices at the watershed scale (Bracmort and others 2006; Parajuli and others 2008). SWAT has also been applied successfully at the field and plot scale (Anand and others 2007; White and others 2009a). The model has been extensively used to evaluate conservation practices in other basins in the state of Oklahoma (White and others 2009b). The SWAT model was also used in the Lake Wister Basin to identify critical source areas for phosphorus and sediment losses (Busteed and others 2009). Given prior research success with SWAT in the basin, it was the only model considered for conservation practice evaluation.

Like any model, SWAT does have limitations. One is the lack of overland flow routing between discretized modeling units. For this reason, SWAT may not adequately account for the deposition and resuspension of sediment and particulate nutrients between upland areas and the stream. Though desirable in many instances, the implementation of landscape level routing would significantly increase the complexity of the model. Another limitation is that SWAT simulates pasture as a monoculture. In reality, most pastures are assemblages of competing species. Despite these limitations, the model is sufficiently accurate for the purpose of conservation practice evaluation at the field and watershed scales and, as previously noted, widely used for this purpose.

Conservation Practices Description

Conservation practice selected for evaluation in this research were generally thought to have a positive impact on vegetative cover thus reducing soil erosion and losses of particulate bound nutrients. Pastures with poor or undesirable vegetation were treated with the establishment of improved forages, including Bermuda and fescue. These areas were generally tilled and fertilized to aid in the establishment of forages though sprigging or seeding. Fields deficient in nutrients for adequate forage production were fertilized at rates based on soil analysis using Oklahoma Cooperate Extension guidelines (Zhang and others 2003). Several conservation practices were designed to alter grazing management. Cross fences were established to allow producers to employ more effective rotation grazing programs that maximized forage utilization. Fencing was also used to limit grazing in sensitive areas like riparian floodplains.

General Methodology

Increasing vegetative cover on the soil surface is an effective method to reduce the loss of sediment (Wischmeier and Smith 1978) and sediment-bound phosphorus (Lemunyon and Gilbert 1993) from pastures. Several conservation practices offered by the OCC were intended to improve vegetative cover and biomass and/or reduce surface runoff. In theory, these practices should reduce overgrazing by increasing forage production and/or limit grazing pressure. In practice, however, a farmer may simply increase stocking rates to take advantage of any additional forage production and continue overgrazing.

To evaluate the effect of these practices on sediment and phosphorus loads an estimate of how each practice affected vegetative cover was required. Vegetative cover can be estimated from remotely sensed data, such as satellite imagery, or measured in the field. For large basins, the use of satellite imagery was more cost effective. Landsat imagery from 2000 to 2004 was analyzed to evaluate changes in pasture vegetation attributable to OCC conservation practices.

The SWAT model can predict nutrient and sediment losses from pastures with differing vegetative cover. SWAT accounts for changes in surface vegetation on sediment losses through the Modified Universal Soil Loss Equation (MUSLE) (Williams and others 1985). The management of surface vegetation also influences plant growth, plant nutrient uptake, residue generation, soil moisture, and soil nutrient cycling. Through these processes, both particulate and nonparticulate phosphorus losses are also influenced. SWAT includes a full crop growth model but has no direct input for vegetative cover or biomass. SWAT allows the user to specify management parameters that govern grazing pressure, allowing the model to simulate a wide variety of vegetative conditions in grazed pasture systems. The minimum biomass for grazing to occur, or BIOMIN, represents the point at which the rancher will limit overgrazing by removing cattle or providing supplemental feed. BIOMIN is measured in units of equivalent dry biomass (kg) per unit area (ha^{-1}). Differences in satellite derived vegetative cover were included in the SWAT model by modifying the BIOMIN parameter. Lower values of BIOMIN allowed more overgrazing to occur; higher values reduced grazing pressure and ensured greater standing biomass during the growing season.

Remotely Sensed Vegetative Cover

Multiple vegetation indices were used to evaluate vegetative cover in treated pastures. The Normalized Difference Vegetation Index (NDVI) is an indicator of photosynthetically active vegetation and has been widely used to estimate biomass (Paruelo and others 1997; Piao and others 2006; Wylie and others 2002). Nongreen biomass and vegetative residues not detected by the NDVI also contribute to surface cover and reduce sediment and phosphorus losses. The Normalized Difference Senescent Vegetation Index (NDSVI) (Qi and others 2002) provides an index of senescent vegetation density and, to a lesser extent, green vegetation density. It has been used successfully in southeast Arizona (Qi and others 2002) for monitoring and managing rangelands and evaluating crop residue in central Iowa (Daughtry and others 2006).

Landsat TM+ images for path 26, row 36, were acquired for 31 August 2004, 28 July 2003, 27 September 2002, 22 July 2001, and 20 August 2000. Image processing was performed using Erdas IMAGINE. Images were radiometrically normalized to allow more meaningful comparison among images using procedures developed by Chander and Markham (2003). These images were georeferenced to 2003 Digital Orthophoto Quarter Quadrangles (DOQQs) with a resolution of 1 m. The NDVI was computed by dividing the difference of the near-infrared (0.83 μm) and visible red (0.66 μm) bands by their sum. The resulting values ranges from −1 to 1; higher values are indicative of photosynthetically active vegetation because the near-infrared band is sensitive to chlorophyll and increases as vegetation becomes greener. The NDSVI was computed by dividing the difference of the shortwave infrared (1.65 μm) and visible red (0.66 μm) bands by their sum. This index was indicative of senescent vegetation because the shortwave infrared band was sensitive to water content and increased as vegetation became drier. The NDVI and NDSVI were used to estimate the relative fractional cover of each pixel covered by green or senescent vegetation using a linear unmixing model that assumed that a pixel was comprised of only vegetation and bare soil. These were calculated using the equations

$$FC_{gv} = (NDVI - NDVI_{soil})/(NDVI_{veg} - NDVI_{soil})$$

$$FC_{sv} = (NDSVI - NDSVI_{soil})/(NDSVI_{veg} - NDVSI_{soil})$$

where FC_{gv} and FC_{sv} are the fraction coverage of green and senescent vegetation, and $NDVI_{soil}$ and $NDVI_{veg}$ are the NDVI values of an area of only bare soil and an area of total vegetation, as derived from an image or measured in the field. The NDVI was also transformed directly to biomass using relationships presented by Wylie and others (2002) for North American grasslands:

$$B = e^{6.26\mathrm{NDVI}+1.17}$$

where B is biomass (g/m^2) and the NDVI is derived from Landsat imagery.

A total of five indicators of vegetative cover or biomass were used in combination to assess vegetative changes from 2000 to 2004 (Table 1). Most of these indicators were derived from summer imagery, and the NDVI and NDSVI both used the visible red (0.66 μm) band. Table 2 lists the Pearson product-moment correlation coefficient among vegetative indicators. Table 2 may be used in future analysis to select only vegetative indicators that provide unique information to reduce the effort required to perform this type of analysis. Some indicators, such as fractional green cover and raw NDVI data, exhibited a high degree of correlation with each other, indicating that they provided similar information. Fractional senescent cover (NDSVI based) and biomass estimated using both summer and winter imagery exhibited less correlation with the other indicators. In particular, fractional senescent cover provided additional information. NDSVI is less commonly used than NDVI based metrics. No measured biomass data temporally coincidental with the satellite imagery were collected. These data would have allowed the performance of these indicators to be evaluated. Without evidence to support a preference for any single indicator, the median value of the five indicators was used to evaluate changes in vegetative cover. The median value was selected as the indicator of central tendency to reduce the influence of outliers.

Vegetative Cover Comparison Methods

Vegetative cover indicators from before the implementation of conservation practices were taken from Landsat imagery captured in 2000; postimplementation data were derived from images captured in 2004. Most of the conservation practices were implemented in this time frame. Changes in vegetative cover during this period may not be attributable to the practices alone. Vegetative cover would have been highly dependent upon environmental and social influences, such as rainfall, temperature, fertilizer cost, stocking rates, and cattle prices. Rainfall differences between 2000 and 2004 would likely yield different biomass levels even under constant management. Due to weather variability, year-to-year comparisons cannot isolate vegetative changes due to conservation practices alone. To address this issue, vegetative indicator values from all pastures in the Wister Lake Basin, even those not included in OCC's programs, were included as a normalizing control variable. These nontreated pastures were assumed to be subject to the same environmental and social influences as pastures that received conservation practices and, thus, acted as a control group.

Vegetative indicators for treated pastures were divided by the average indicator value for all nontreated pastures within each Landsat image to generate a normalized ratio. A ratio of 1 indicated that biomass in a treated pasture was

Table 1 Normalized Difference Vegetation Index (NDVI)- and Normalized Difference Senescent Vegetation Index (NDSVI)-based metrics used to evaluate vegetative cover before and after the implementation of conservation practices in the Lake Wister Basin

Metric	Preimplementation image(s)	Postimplementation image(s)
NDVI-estimated biomass	Summer and winter 2000	Summer and winter 2004
NDVI-estimated biomass	Summer 2000	Summer 2004
Raw NDVI	Summer 2000	Summer 2004
Fractional green cover (NDVI based)	Summer 2000	Summer 2004
Fractional senescent cover (NDSVI based)	Summer 2000	Summer 2004

Table 2 Landsat vegetative cover indicator correlation matrix: based on the Pearson product-moment correlation coefficient

	NDVI biomass (summer and winter)	NDVI-estimated biomass (summer)	Raw NDVI (summer)	Fractional green cover (summer)
NDVI biomass (summer)	0.81	–	–	–
Raw NDVI* (summer)	0.66	0.82	–	–
Fractional green cover (summer)	0.67	0.80	0.97	–
Fractional senescent cover (summer)	0.25	0.36	0.39	0.41

Note: *NDVI* Normalized Difference Vegetation Index similar to that in nontreated pastures within a single satellite image. If unfavorable weather reduced the biomass production on a treated pasture, it would have also reduced biomass production on nearby nontreated pastures by a similar amount, thus maintaining a ratio of 1. Therefore, changes in the normalized ratio on treated pastures from 2000 to 2004 were assumed to be entirely attributable to the establishment of conservation practices. Figure 2 illustrates the change in normalized green biomass from 2000 to 2004 in a single treated field.

Landsat imagery was also used to evaluate all pastures in the basin to identify pastures with consistently less surface biomass than average for the purposes of targeting future conservation practices. Reduced biomass in pastures is likely the result to overgrazing or recent haying. NDVI-estimated green biomass was averaged across all available imagery. The results (Fig. 3) indicate that pastures in Latimer County had 16% less biomass than those in LeFlore County. The difference may be due to differences in poultry house density, resulting in far greater availability of poultry litter for pasture fertilization in the LeFlore County. This type of analysis would ideally have been used to identify consistently low biomass fields (indicative of overgrazing) prior to the implementation of conservation practices in the basin. Targeting establishment of conservation practices may improve the potential effectiveness of conservation programs (White and others 2009b). Although the SWAT model was initially used to identify critical source areas in the Lake Wister Basin (Storm and others 2006), the analysis did not include these Landsat-derived biomass data. Use of these data may increase the accuracy of targeting critical source areas at the basin scale.

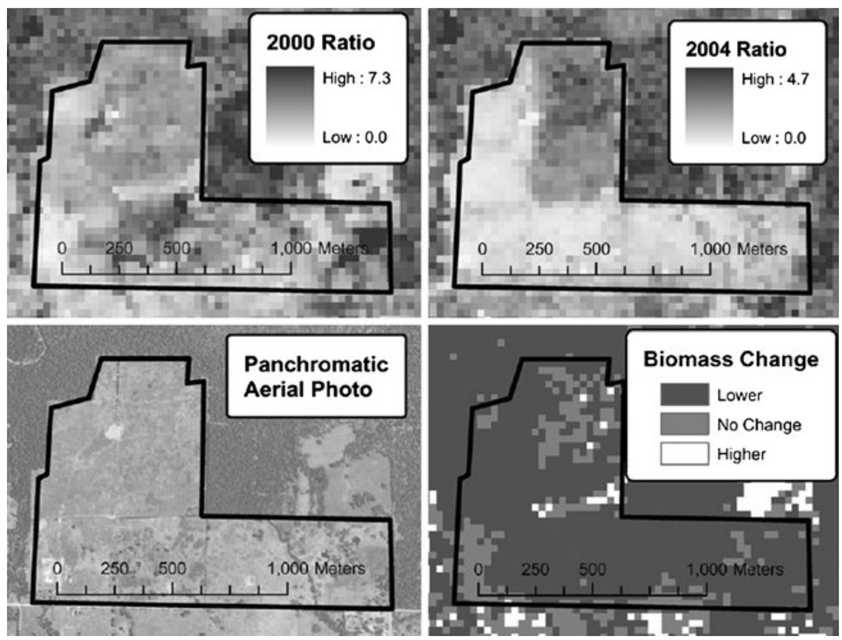

Fig. 2 Example field receiving fertilizer and lime. Biomass ratio (30-m resolution) in summer 2000 (*upper left*) and summer 2004 (*upper right*), where a *darker shade* indicates a higher relative biomass. Aerial photo (2-m resolution; *bottom left*) captured in 2003. Environmentally corrected biomass change map (*bottom right*) shows areas with lower, higher, and no significant change (±25%) from 2000 to 2004. The field had a mean loss of 77% of its relative biomass during this period

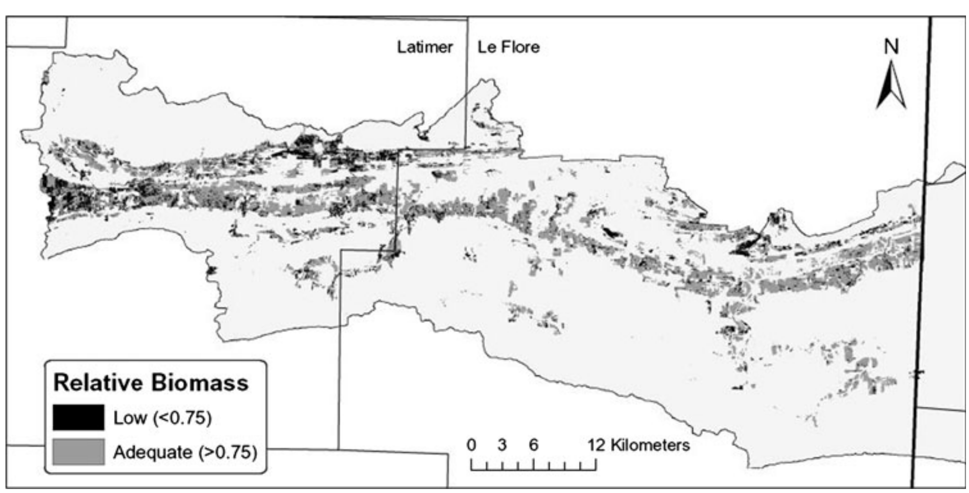

Fig. 3 Estimated biomass trend over 5 years (2000–2005) using Landsat imagery for all pastures in the Oklahoma portion of the Wister Lake Basin. Pastures with less than 75% of the average biomass were categorized as low-biomass pasture

Simulating Sediment and Phosphorus Yields Using SWAT

The SWAT model was used to simulate changes in phosphorus and sediment yields due to the implementation of conservation practices on 175 fields in the Lake Wister Basin. A SWAT model with a single subbasin was developed for each field. To predict the effect of conservation practice establishment, two scenarios were performed. A preprogram simulation was developed to predict the sediment and phosphorus yields from each field prior to the implementation of any conservation practices associated with the OCC program. The postprogram simulation included the new conservation practices and updated vegetative cover derived from the satellite image analysis. The differences in sediment and phosphorus losses between the two simulations were attributed directly to the OCC-sponsored conservation practices.

Preprogram Simulation

Each model included topographical data estimated using a 30-m resolution data and soil data from the Natural Resource and Conservation Service (NRCS) Soil Survey Geographic SSURGO database (USDA 1991). Measured daily rainfall and minimum and maximum temperature from 1 January 1999 to 31 December 2003 were used. Soil phosphorus content was derived from measured Mehlich III extractable phosphorus from samples collected from each field. The average county soil test phosphorus was used to represent fields which were not sampled. The majority of unsampled fields were in areas with little history of poultry litter application and should be well represented by the county average.

Typical management for grazed grassland was derived from interviews with local conservation district and NRCS personnel. All fields were grazed as continuous cow-calf operations. SWAT contained a full plant growth routine and simulated forage production and consumption by cattle on a daily basis. Stocking rate was derived from interviews with local Oklahoma Cooperative Extension Service agents and was assumed to be 0.41 animal unit per hectare. Stocking rate was only one of the variables used to represent grazing in SWAT. The minimum biomass for grazing to occur, i.e., BIOMIN, represented the point at which the rancher limited overgrazing by removing cattle or providing supplemental feed. Unfortunately, it was not possible to determine an accurate estimate of BIOMIN for preprogram simulations. Ideally, measured biomass temporally coincidental with at least one of the Landsat images would have allowed the development of a relationship between biomass and the vegetative indicators. The relationship provided by Wylie and others (2002), while useful for relative comparisons, was not developed in this ecoregion and may not be sufficiently accurate for absolute predictions of biomass. A single value for the pretreatment BIOMIN was not justifiable. Therefore, a series of simulations was performed assuming pretreatment BIOMIN values from 700 to 1,500 kg ha^{-1} at 100 kg ha^{-1}intervals. Tall Fescue had a recommended minimum residual of 10–13 cm in height (Bidwell and Woods 1996) to maintain stand persistence and animal production. Good condition mixed forage pasture contained about 88 kg ha^{-1} cm^{-1} (Barnhart 1998). Given these estimates, good condition pasture would contain a minimum of 1,000 kg ha^{-1}. The range in BIOMIN roughly represented values from moderate overgrazing to underutilization of forage.

To better account for local conditions, all SWAT simulation included model parameters derived from a calibrated SWAT model of the entire Lake Wister Basin (Storm and others 2006; Busteed and others 2009). This model was calibrated to measured sediment and phosphorus data collected at stream gages throughout the basin. Though not calibrated for each field, the use of localized calibration parameter data should improve the accuracy of this analysis.

Postprogram Simulation

Postprogram simulations were based directly on the preprogram data with the addition of the OCC conservation practices. The relative difference in vegetative cover attributable to OCC practices was applied by changing BIOMIN in the postprogram simulations. Because multiple simulations were performed to represent varying levels of preprogram BIOMIN, multiple postprogram simulations were also performed.

Fields receiving the fescue seeding treatment were assumed to be converted to a grazed tall fescue. Fields sprigged with Bermuda were simulated as grazed Bermuda in the postprogram simulation. Most of the fields receiving these two forage establishment treatments also received fertilizer to aid in stand establishment. The application of fertilizers to improve forage condition was a popular conservation practice. Fertilized fields received rates of nitrogen and phosphorus reported by OCC records. Commercial phosphorus fertilizer was applied as a conservation practice despite the project focus on reducing phosphorus loads to Lake Wister. Fertilizer application was based on agronomic soil test recommendations for Oklahoma forages by Zhang and others (2003). To predict the effectiveness of the program had it not included phosphorus fertilizers, a second set of simulations was performed without phosphorus application.

Limited grazing required no additional adjustments for postprogram simulation, as grazing rate was controlled directly by BIOMIN and adjusted to account for changes in vegetative cover. Likewise, cross-fencing effects were represented by changes in vegetative cover only. The establishment of cross fencing was intended to allow producers to better manage cattle distribution through rotation grazing programs. Since the SWAT model does not adjust forage growth based on soil pH, the effects of lime treatments were determined by changes in vegetative cover only.

Custom software written in Microsoft Visual Basic 6.0 was used to automate the modeling process. Each of the 175 fields was represented in SWAT as a single subbasin model. A total of 4725 model runs was required, encompassing one set of preprogram conditions, two sets of postprogram conditions (with and without phosphorus application), and nine levels of BIOMIN.

Results

Changes in Vegetative Cover

On average, fields treated with any combination of conservation practices exhibited a slight increase (1.9%) in vegetative cover from the summer of 2000 to the summer of 2004. However, some practices resulted in reduced vegetative cover. Fields receiving fertilizer alone increased vegetative cover by 7.7% (see Table 3). Fields receiving cross fencing, fertilization, and lime increased vegetative cover by 18%. Practices including the planting of fescue or Bermuda sprigging exhibited large decreases in biomass. These areas were poor-condition pastures that were tilled and seeded with fescue or sprigged with Bermuda. In several fields, it was likely that these forages had not been fully established by the capture of the postimplementation imagery in the summer 2004. Therefore, fields receiving this treatment in 2004 were assumed to be in transition and were removed from the analysis.

Table 3 Median change in five indicators of vegetative cover before and after the implementation of conservation practices in the Lake Wister Basin: based on 2000 and 2004 Landsat imagery

Practice(s)	Treated area (ha)	Vegetative cover change (%)
Planting fescue	11	–41
Fertilization only	524	7.7
Limited grazing	72	2.2
Lime only	132	–4.7
Bermuda sprig	20	–19
Lime and fertilization	846	2.0
Fertilization and Bermuda	9	25
Lime and fescue	120	–40
Cross fence	1,010	3.4
Fence and fertilization	113	1.5
Fence and lime	11	20
Fence, lime, and fertilization	111	18
Fence and Bermuda	12	–11
Fence, fertilization, and Bermuda	20	12
Limit grazing and fence	2	–39
Overall	3,014	1.9

Changes in vegetative cover within each conservation practice treatment type were variable. A portion of this variation was due to the use of only a few Landsat images to characterize vegetative cover. A single instant in time may not fully characterize the average condition of the field. Haying or flash grazing just prior to image capture may result in an uncharacteristically low estimate of surface cover. The field depicted in Fig. 2 is an example of a treated field which appeared to be hayed prior to image capture in 2004. The use of additional satellite images could have provided a better indication of the average field condition both before and after treatment with conservation practices.

Sediment and Phosphorus Reductions

SWAT predicted a 20% (Fig. 4) and a 65% reduction in phosphorus and sediment losses from treated fields at low preimplementation BIOMIN, respectively. At higher initial BIOMIN values, these vegetative conservation practices were predicted to increase phosphorus loss from these fields by as much as 60%. The increase was the result of phosphorus fertilizers which were utilized as a conservation measure in the program. Simulations without the addition of phosphorus fertilizers yielded much larger reductions in phosphorus losses from treated fields, ranging

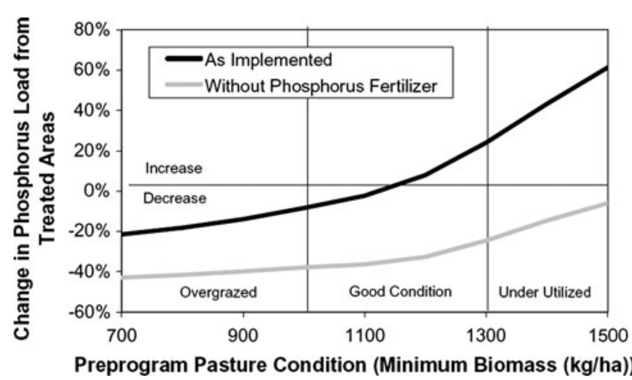

Fig. 4 Predicted changes in phosphorus load from fields treated with fertilization as a function of assumed pretreatment BIOMIN (pasture condition). Based on SWAT predictions and vegetation indices derived from Landsat imagery collected before and after the implementation of conservation practices. Changes in phosphorus loads given both as implemented and with the exclusion of phosphorus fertilizer from the program

from 40 to 5%. Initial assumptions of BIOMIN had less influence predicted change in sediment losses.

The model predicted the application of fertilizer reduced phosphorus loss but only if the pasture already had poor surface cover (low BIOMIN). Fertilization reduced phosphorus loss only if the preimplementation surface cover (BIOMIN) was less than 1100 kg ha^{-1} (Fig. 4). Poor surface cover generates greater sediment losses and particulate phosphorus transport. Phosphorus contained in the soil may be transported in sediment-bound forms with the eroded soil. Fortunately, areas in this basin with high erosion were of low fertility; the soils contained little phosphorus. The effect of nitrogen fertilizer additions to improve productivity would be much more important on poor-condition fields with high soil phosphorus levels. Nitrogen added to well-managed pasture may increase forage productivity and cattle grazing. The additional cattle produce more manure, which in turn increases phosphorus losses. Many pastures in eastern Oklahoma have elevated soil phosphorus due to a history of poultry litter application. If litter application is halted without supplemental nitrogen fertilizer and the field is overgrazed, the field could become a very large source of sediment-bound phosphorus. This is of particular interest in areas where the application of poultry litter is suddenly restricted. Ranchers accustomed to free or low-cost poultry litter may not opt to pay for commercial nitrogen.

The model predicted that nitrogen fertilizer applied to good condition pastures may have little benefit to pollutant losses. The application of nitrogen to poor condition pasture (BIOMIN = 700 kg ha^{-1}) reduced phosphorus loss by 43%, while application to underutilized pasture (BIOMIN = 1,500 kg ha^{-1}) reduced losses by only 6% (Fig. 4). Phosphorus loss from pastures with good cover was primarily soluble and not associated with eroded soil particles. Increasing the productivity with additional nitrogen may further reduce erosion and sediment-bound phosphorus loss but may not reduce soluble phosphorus losses. Furthermore, increased productivity is generally accompanied by higher stocking densities. More animals grazing means more manure on the soil surface and potentially higher soluble phosphorus losses.

The overall effect on sediment and phosphorus loads to Lake Wister was relatively small, primarily due to the limited extent of the conservation practices examined in this research. Only 1.25% of the basin was treated; the SWAT model predicted that about 5% of the sediment and phosphorus loads originated from this area. SWAT predicted that the sediment load to Lake Wister was reduced by 3.3%. Phosphorus load reduction was much more sensitive to assumed preimplementation pasture condition (BIOMIN). Since this value was unknown, a range of phosphorus loads was predicted. With the best-case scenario, i.e., a low initial BIOMIN, the total phosphorus load to Lake Wister was predicted to be reduced by 1%. With a precondition BIOMIN value greater than 1,100 kg/ha, there were increased phosphorus loads predicted and no net benefit of conservation practices in terms of phosphorus losses.

Discussion

This was the first time the water quality benefits of an implementation cost-share program were quantified using modeling and remote sensing in Oklahoma. This research demonstrated that it was possible to evaluate some practices after the program was complete, but the collection of measured biomass at randomly selected sites could significantly reduce the uncertainty in these predictions. The vegetative cover analysis showed promise in evaluating the effects of vegetative conservation practices and the identification of overgrazed pastures. These methods allowed large areas to be analyzed quickly with consistency using relatively low-cost Landsat imagery. Given sufficient images, areas of consistently poor biomass from year to year can be identified at the basin scale. The active recruitment of landowners with poor condition pastures into conservation programs may improve total program effectiveness and thus downstream water quality. OCC's conservation programs were voluntary; landowners ultimately decided which practices they adopted. Also, nothing guaranteed the implementation of practices that were deemed high priority, or that implementation occurred in the targeted areas. The vegetative practices evaluated in this study were popular, even though other practices may have been more effective.

Based on these model simulations, we do not recommend the application of phosphorus fertilizers as a conservation measure for phosphorus loss. Even soils with low soil test phosphorus can support modest forage production. At a Mehlich III soil test phosphorus of 5 mg kg^{-1}, Bermuda has a phosphorus sufficiency of 50% (Zhang and others 2003); i.e., forage production is reduced by half due to phosphorus limitations. To entirely eliminate phosphorus deficiencies, a soil test phosphorus value of 33 mg kg^{-1} is required. In Latimer County, where the majority of pastures were phosphorus deficient, soil test phosphorus averaged 15 mg kg^{-1} (88% sufficiency). The addition of phosphorus fertilizers in these conditions only increased the forage yield by 12% but significantly increased the total phosphorus load leaving the field (Fig. 4). There may be a benefit from applying phosphorus fertilizers to fields with very low soil test phosphorus ($<$10 mg kg^{-1}) if the fields are severely eroding and the increase in fertility is enough to prevent erosion. It is a practice that should be used with caution since the long-term effects are unknown, and most of the phosphorus will reside in the soil for many years after application.

The selection of appropriate conservation practices is both difficult and critical to the success of conservation programs, which at their outset are already limited by the extent, nature, and spatial occurrence of landowner participation. A summary of all vegetation analysis, once corrected for environmental factors, indicated only a slight increase in vegetation, and the small reduction in pollutant loads was attributable to the conservation program. It is difficult to judge which conservation practices will be successful a priori; some practices, such as fertilization, certainly prompted farmers to simply increase stocking rates, thus reducing any net increase in vegetation. This approach offers an opportunity to explore the effectiveness of different conservation practices and may provide guidance for the selection of conservation measures subsidized in future conservation programs.

Acknowledgments We would like to thank the Oklahoma Conservation Commission, U.S. Environmental Protection Agency region VI, and Oklahoma State University for funding this research. We would also like to thank Leflore and Latimer County conservation district and U.S. Natural Resources and Conservation Service personnel for their assistance with local aspects of this project.

References

Anand S, Mankin KR, McVay KA, Janssen KA, Barnes PL, Pierzynski GM (2007) Calibration and validation of ADAPT and SWAT for field-scale runoff prediction. Journal of the American Water Resources Association 43:899–910

Arnold JG, Srinivasan R, Muttiah RS, Williams JR (1998) Large area hydrologic model development and assessment part 1: Model development. Journal of the American Water Resources Association 34:73–89

Barnhart SK (1998) Estimating available pasture forage. Iowa State University, Extension publication PM1758. Available at: http://www.extension.iastate.edu/Publications/PM1758.pdf. Accessed August 25, 2009

Bidwell T, Woods B (1996) Management strategies for rangeland and introduced pastures. Oklahoma Cooperate Extension Service publication NREM-2869. Available at: http://pods.dasnr.okstate.edu/docushare/dsweb/Get/Document-2564/NREM-2869web.pdf. Accessed August 25, 2009

Bishop PL, Hively WD, Stedinger JR, Rafferty MR, Lojpersberger JL, Bloomfield JA (2005) Multivariate analysis of paired watershed data to evaluate agricultural best management practice effects on stream water phosphorus. Journal of Environmental Quality 34:1087–1101

Bracmort KS, Arabi M, Frankenberger JR, Engel BA, Arnold JG (2006) Modeling long-term water quality impact of structural BMPs. Transactions of the ASAE 49:367–374

Busteed PR, Storm DE, White MJ, Stoodley SH (2009) Using SWAT to target critical source sediment and phosphorus areas in the Wister Lake basin. American Journal of Environmental Sciences 5:156–163

Chander G, Markham BL (2003) Revised Landsat-5 TM radiometric calibration procedures and postcalibration dynamic ranges. Institute of Electrical and Electronics Engineers Transactions on Geoscience and Remote Sensing 41:2674–2677

Chu T, Shirmohammadi A, Abbott L, Sadeghi A, Montas H (2005) Watershed level BMP evaluation with SWAT model. In: Proceedings of the 2005 ASAE Annual International Meeting, St. Joseph, MI, paper no. 052098

Daughtry CST, Doraiswamy PC, Hunt JER, Stern AJ, McMurtrey JE III, Prueger JH (2006) Remote sensing of crop residue cover and soil tillage intensity. Soil Tillage Research 91:101–108

Djodjic F, Montas H, Shirmohammadi A, Bergstrom L, Ulen B (2002) A decision support system for phosphorus management at a watershed scale. Journal of Environmental Quality 31:937–945

Gassman PW, Reyes MR, Green CH, Arnold JG (2007) The Soil and Water Assessment Tool: historical development, applications and future research directions. Transactions of the ASAE 50:1211–1250

Gitau MW, Veith TL, Gburek WJ (2004) Farm-level optimization of BMP placement for cost-effective pollution reduction. Transactions of the ASAE 47:1923–1931

Gitau MW, Gburek WJ, Jarrett AR (2005) A tool for estimating best management practice effectiveness for phosphorus pollution control. Journal of Soil and Water Conservation 60:1–10

Hardy SD, Koontz TM (2008) Reducing nonpoint source pollution through collaboration: policies and programs across the U.S. States. Environmental Management 41:301–310

Lemunyon JL, Gilbert RG (1993) The concept and need for a phosphorus assessment tool. Journal of Production Agriculture 6:483–486

Oklahoma Conservation Commission (2008) Spavinaw Creek watershed implementation project final report. Oklahoma Conservation Commission, Water Quality Division, Oklahoma City

Oklahoma Water Resources Board (1996) Diagnostic and feasibility study of Wister Lake: phase I of a clean lakes project—final report. Oklahoma Water Resources Board, Oklahoma City

Oklahoma Water Resources Board (2003) Lake Wister water quality, bathymetry, and restoration alternatives—final report. Oklahoma Water Resources Board, Oklahoma City

Omernik JM (1987) Ecoregions of the conterminous United States. Annals of the Association of American Geographers 77:118–125

Parajuli PB, Mankin KR, Barnes PL (2008) Applicability of targeting vegetative filter strips to abate fecal bacteria and sediment yield using SWAT. Agricultural Water Management 95:1189–1200

Paruelo JM, Epstein HE, Lauenroth WK, Burke IC (1997) ANPP estimates from NDVI for the central grassland region of the United States. Ecology 78:953–958

Piao S, Mohammat A, Fang J, Cai Q, Feng J (2006) NDVI-based increase in growth of temperate grasslands and its responses to climate changes in China. Global Environmental Change 16:340–348

Pierson ST, Cabrera ML, Evanylo GK, Kuykendall HA, Hoveland CS, McCann MA, West LT (2001) Phosphorus and ammonium concentrations in surface runoff from grasslands fertilized with broiler litter. Journal of Environmental Quality 30:1784–1789

Qi J, Marsett R, Heilman P, Biedenbender S, Moran S, Goodrich D, Weltz M (2002) RANGES: improves satellite-based information and land cover assessments in southwest United States. EOS, Transactions of the American Geophysical Union 83(51):601–606

Sauer TJ, Daniel TC, Nichols DJ, West CP, Moore PA Jr, Wheeler GL (2000) Runoff water quality from poultry litter-treated pasture and forest sites. Journal of Environmental Quality 29:515–521

Storm DE, Busteed PR, White MJ, Stoodley S, Berasi B (2006) Wister Lake basin targeting and cost share program evaluation. Department of Biosystems and Agricultural Engineering, Oklahoma State University, Stillwater. Available at: http://storm.okstate.edu/reports/Wister%20Final%20Report%2010-19-2006.pdf. Accessed March 18, 2009

TetraTech (2005) User's guide: spreadsheet tool for the estimation of pollutant load (STEPL). U.S. Environmental Protection Agency. Available at: http://it.tetratech-ffx.com/stepl/STEPLmain_files/STEPLGuide310.pdf. Accessed March 18, 2009

USDA (1991) Soil Survey Geographic (SSURGO) database: data use information. Misc. Publ. 1527, U.S. Department of Agriculture, Washington, DC

USEPA (1993) Paired watershed study design. Document 841-F-93–009. U.S. Environmental Protection Agency, Washington, DC

USEPA (2007) Clean Water Act Section 319(h) grant funds history. U.S. Environmental Protection Agency. Available at: http://www.epa.gov/owow/nps/319hhistory.html. Accessed March 18, 2009

USNRCS (2009) Conservation Effects Assessment Project (CEAP). Available at: http://www.nrcs.usda.gov/technical/nri/ceap/. Accessed March 18, 2009

Vache KB, Eilers JM, Santelmann MV (2002) Water quality modeling of alternative agricultural scenarios in the U.S. Corn Belt. Journal of the American Water Resources Association 38:773–787

White MJ, Storm DE, Smolen MD, Zhang H (2009a) Development of a quantitative pasture phosphorus management tool using the SWAT model. Journal of the American Water Resources Association 45:397–406

White MJ, Storm DE, Busteed PR, Stoodley SH, Phillips SJ (2009b) Evaluating nonpoint source critical source area contributions at the watershed scale. Journal of Environmental Quality 38:1654–1663

Williams JR, Nicks AD, Arnold JG (1985) Simulator for water resources in rural basins. Journal of Hydraulic Engineering 111:970–986

Wischmeier WH, Smith DD (1978) Predicting rainfall erosion losses agricultural handbook 537. U.S. Department of Agriculture, Washington, DC

Wylie BK, Meyer DJ, Tieszen LL, Mannel S (2002) Satellite mapping of surface biophysical parameters at the biome scale over the North American grasslands: a case study. Remote Sensing of Environment 79:266–278

Zhang H, Johnson G, Raun B, Basta N, Hattey J (2003) Fact sheet 2225. OSU soil test interpretations. Oklahoma State University, Stillwater

Zinn J, Canada AC (2007) Environmental Quality Incentives Program (EQIP) status and issues. Congressional Research Service, Library of Congress, Washington, DC