A Landscape-Level Geographic Information System (GIS) Analysis of Streamside Management Zones on the Cumberland Plateau

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ABSTRACT

In this study, we developed and tested a geographic information system methodology to measure the width and slope of streamside management zones (SMZs). We also assessed the compliance of SMZs on the Cumberland Plateau of Tennessee with the quantitative portions of state best management practices and the sustainable forestry standards used by the Sustainable Forestry Initiative and the Forest Stewardship Council (FSC). We found that using different standards greatly affected overall SMZ compliance and that FSC-level compliance varied as a function of type and resident status of forest owner.

Keywords: sustainable forestry, GIS, Streamside Management Zones, Best Management Practices, riparian buffers, remote sensing

Streamside management zones (SMZs), or riparian buffers, have been shown to play an important role in mitigating the effects of forestry operations on water quality and ecosystems. Because their efficacy is at least partially linked to their width, measuring the widths of SMZs across an entire landscape may provide an important indicator of sustainable forestry, water quality, and ecological integrity (e.g., Wenger [1999], Sponseller et al. [2001], Kiffney et al. [2003], Lee et al. [2004]). Geographic information systems (GIS) may enable precise measurement of SMZ widths through the use of remote sensing technologies.

State best management practices (BMPs) were developed to mitigate the environmental effects of timber harvesting and have served as a basis for establishing forestry certification standards. The verification of BMP compliance requires field visits that are both time and labor intensive. The SMZ guidelines in BMPs often emphasize quantitative relationships between the slope of the land and minimum SMZ widths, and these quantitative relationships could be assessed with GIS and remote sensing technologies. Such a GIS assessment may be more efficient than field visits at estimating the BMP compliance of SMZs for large areas.

To our knowledge, no prior studies have used a GIS approach to measure actual SMZs across a landscape. Previously, GIS approaches have been used to analyze land use or vegetative cover within a predefined buffer around streams (e.g., Narumalani et al. [1997], Perry et al. [1999]) or to determine how wide SMZs in particular locations should be (e.g., Xiang [1996], Bren [2000]). The objective of this study was to develop a GIS methodology to measure the actual width and slope of SMZs and to apply this technology to assess compliance with quantitative SMZ standards on blue line streams in recently harvested lands on the southern Cumberland Plateau of Tennessee.

The Study Area

The southern Cumberland Plateau of Tennessee is a biologically diverse area that has experienced a high rate of forest conversion as portions of its oak-hickory hardwood forest have been cleared for loblolly pine plantations, residential development, and pasture (McGrath et al. 2004). In addition, some hardwood forestry activity on the southern Cumberland Plateau recently has involved the use of area-intensive clearcutting. This study examined 567,259 acres of Tennessee plateau surface in the six counties of Bledsoe, Grundy, Marion, Sequatchie, Van Buren, and Warren. Areas that had been harvested between 2000 and 2003 were identified by comparing a Landsat classification for 2003 with a land use/land cover classification for 2000 (Evans et al. 2002). We were interested in all areas that were covered by native forest or pine in 2000 and that had been logged or cleared by 2003.

Study Methods

A GIS-based analytical tool was created using ESRI's ArcGIS 8.3 (Redland, CA) and an ArcGIS macro that we developed specifically for this study. Scanned and rectified

Farm Service Agency (FSA) aerial photographs from 2003 provided 1- to 2-m resolution imagery for digitizing SMZs. We used FSA imagery because it is publicly and widely available and within the reach of a broad set of users. A slope percentage raster layer was created from US Geological Survey (USGS) 10-m digital elevation models (DEMs). The slope values derived from these DEMs should be "roughly the same" as those derived from higher-resolution DEMs (Moglen and Hartman 2001).

Every time a stream represented as a blue line on a USGS 1:24,000 quad map passed through a recently harvested site in the six-county study area, we digitized the SMZ from the FSA imagery by drawing a polygon around its boundary. One-sided SMZs, where the blue line stream was part of a border with native forest or with a nonforestry land use, were not included in this study. Where the blue line stream was part of a border with native forest, the location of the stream was not known with sufficient precision to measure the distance from the edge of the stream to the edge of the forest. Where the blue line stream was part of a border with a nonforestry land use, it was not always clear whether the responsibility for the SMZ lay with foresters and thus whether applying forestry BMPs and standards would be appropriate. In pine plantations, SMZs were delineated by the buffer of hardwoods or mature pine. Where an SMZ was interrupted by an unnamed logging road of greater breadth than 16.4 ft (5.0 m) or where an SMZ simply did not exist for a significant distance along a blue line stream, a separate polygon of arbitrary width was drawn around the stream path and assigned a special code to indicate that no SMZ was present.

We defined a single SMZ as the riparian buffer along a continuous reach of blue line stream in a harvested area. In the field, the width may have varied considerably along such a reach of stream, and calculating the average width and slope for such a unit could obscure information about segments of the SMZ. We therefore wrote GIS scripts to cut each SMZ at points placed every 50.0 m (164.0 ft) along the stream path. Hereafter, the original polygons will be called "whole SMZs" (Figure 1). These 50-m sections were then split along the stream path to form what we designate as "GIS sections" (Figure 1). Because USGS blue lines were not precise enough to define a stream path and because the lack of precise orthorectification for the FSA imagery reduced the utility of DEM-derived streams, we used centerlines drawn down the middle of each whole SMZ to represent the stream path. Because an assumption about the stream path must be made, the assumption that it follows the middle of the SMZ seemed to be the safest and the most conservative.

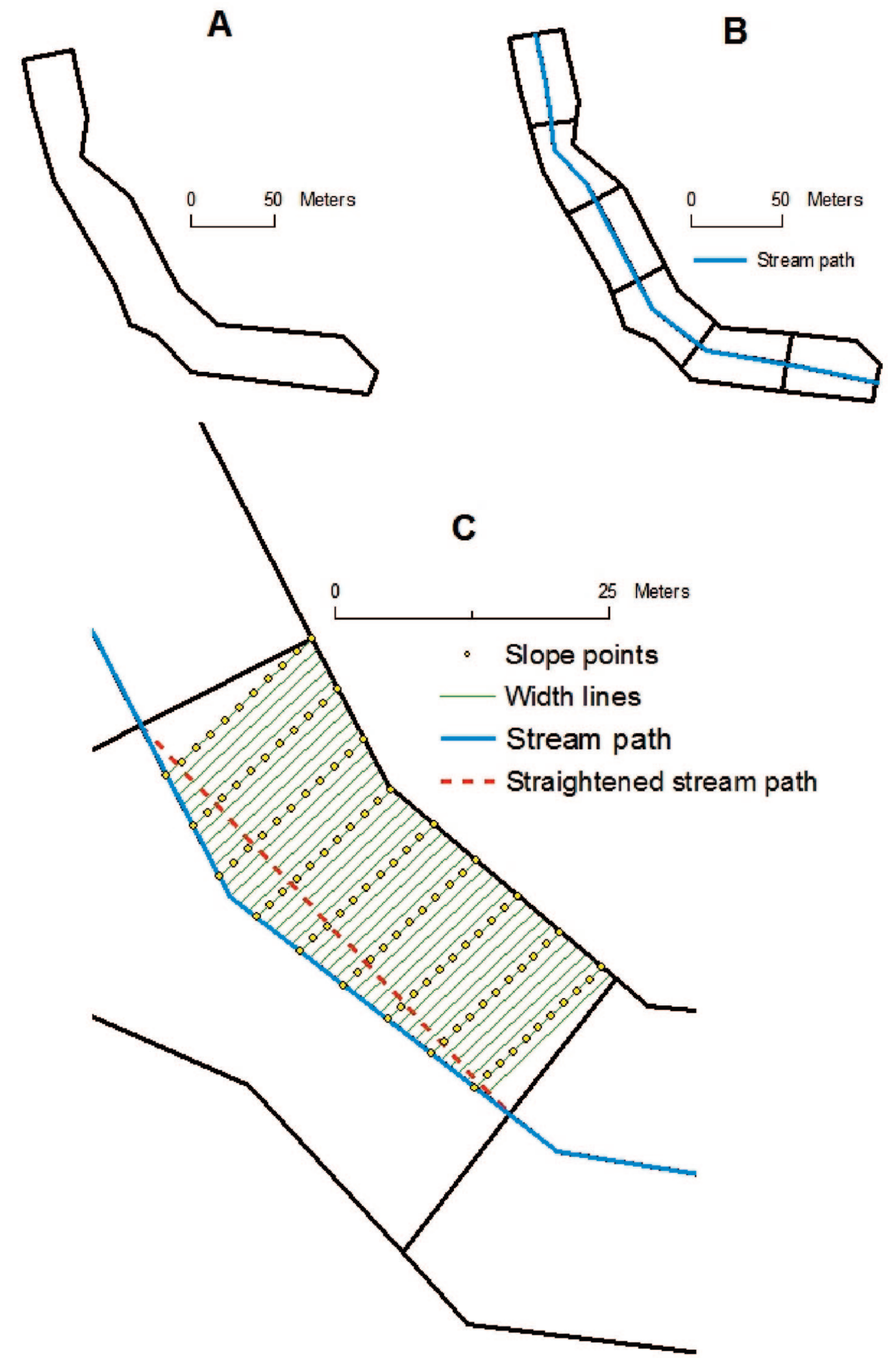


Figure 1. Polygons represent SMZs and illustrate how the macro works to calculate the width and slope of SMZs: (A) a polygon representing a "whole SMZ"; (B) the whole SMZ polygon divided into "GIS sections" at every 50.0 m (164.0 ft) along its stream path, with the stream path also serving as a dividing line; (C) the width lines that the macro uses to calculate the average width of one GIS section, and the points at which it references a slope percentage raster layer to calculate the average slope percentage of the GIS section.

The 50-m GIS sections and the slope percentage raster layer were used by the macro as inputs to obtain the average width and average slope for each polygon. To calculate the average transverse width of a GIS section, the macro created "width lines" at every meter along the stream path and clipped the width lines to the border of the SMZ (Figure 1). Averaging the lengths of the width lines provided the width of the SMZ. One question that arose concerned the proper angle that the width lines must take relative to the stream path to measure transverse width. If the width lines were created perpendicular to the stream path, then a curve in the stream path (as in Figure 1) would have led to angled width lines that may have crossed each other and that would not have represented the ordinary conception of transverse width as applied in the field. To avoid this problem, we programmed the macro to create a straight line that connected the two end points of the stream path where it entered and exited the GIS section. This straightened stream path, represented by the dashed line in Figure 1, was used as a reference to determine the angle of perpendicularity for the GIS section. This resulted in width lines that were not redirected by curves in the stream path and so were perpendicular at a consistent, reasonable angle.

For every fifth width line, the macro referred to the raster layer to obtain the slope percentage at 11 points—1 at the stream path and 10 more spaced evenly along the width line at intervals of one-tenth of the length of the width line (Figure 1). We chose to use 11 points because we had to compromise between processing time and sample density. Given the typical width of SMZs and the 10-m resolution of the slope percentage raster layer, this number of sample points should have included all the raster pixels that any width line intersected for a significant distance. These 11 slope percentages were averaged to obtain the slope percentage for the width line, and the slope percentages for every fifth width line were averaged to obtain the slope percentage for the GIS section. The width lines used for slope calculations therefore were separated by 5 m along the stream path, which is within the 10-m cell size of the slope percentage raster layer. We decided to calculate slope for every fifth width line because using every width line would have greatly increased processing time without appreciably increasing accuracy. As explained previously, a special code was used to indicate the absence of an SMZ in the GIS section. In this case, the macro assigned the polygon a width of zero and did not calculate slope.

Table 1. SMZ standards used in this study.

BMPs/SFI		FSC	
Slope of SMZ	Minimum width (ft)	Slope of SMZ	Minimum width (ft)
0–9%	25	1–10%	80
10–19%	45	11–20%	100
20–29%	65	21–30%	130
30–39%	85	31–40%	135
40–49%	105	>40%	165
50–59%	125		
≥60%	145		

Notes: We used only the quantitative portion of each standard. The widths refer to the minimum buffer width on one side of the stream. SFI refers to state BMPs (SFI Program et al. 2002), which for Tennessee are voluntary guidelines (Tennessee Division of Forestry, Department of Agriculture 2003). FSC developed SMZ standards for its Appalachia region (FSC 2003).

As a framework to categorize and analyze the width and slope data, we employed the SMZ standards used by the state of Tennessee and two sustainable forestry certification programs: the Sustainable Forestry Initiative (SFI) and the Forest Stewardship Council (FSC). The Tennessee state BMPs are voluntary guidelines (Tennessee Division of Forestry, Department of Agriculture 2003). SFI's SMZ standard specifies compliance with state BMPs (The SFI Program et al. 2002). FSC's SMZ standard for the Appalachia region, of which the study area is a part, requires greater widths than do state BMPs/SFI (FSC 2003). Although state BMP or SFI standards currently are applied by some landowners in the study area, the evaluation of compliance with state BMPs/SFIs often is hypothetical, and the evaluation of compliance with FSC is always hypothetical because no private landowners in the region were known to be using that standard as of 2003.

The BMP/SFI compliance and FSC compliance of each GIS section were determined by comparing the average width and slope with the standards' thresholds (Table 1). These GIS sections also were regrouped into whole SMZs to obtain SMZ-level compliance data and were combined with county tax information to obtain parcel-level compliance data. We did not measure full compliance of SMZs with any standard, because that may involve evaluating management plans, checking for special situations such as natural disasters, and monitoring selective harvesting. Using the state BMP/SFI and FSC standards enabled us to classify the width and slope data in a meaningful manner, but as will be discussed, the errors introduced through the FSA imagery mean that the compliance results given here should be taken as no more than a rough guide to the status of SMZs on the Cumberland Plateau. In this article, SMZs are said to be "compliant" or "noncompliant" only in the limited sense of how the width and slope data collected for this study relate to the quantitative portions of the SMZ standards.

Accuracy Assessment

The slope and width data calculated by the macro could be adversely affected by the quality of the imagery and by imprecise digitization. To assess the magnitude of this effect, we field checked both data sets and used one-sample *t*-tests on the difference between the original GIS values and the new values derived through fieldwork.

We checked the accuracy of slope data by taking slope measurements with clinometers in the field every 10 m along the stream paths of 10 GIS sections. We found no statistically significant difference between the slope percentage values as measured with the GIS macro and those values as measured in the field ($P = 0.17$, 9 degrees of freedom [df]).

We field checked width data by walking the boundaries of two whole SMZs on different tax parcels with a Leica RS500 global positioning systems (GPS) unit (Leica Geosystems AG, Heerbrugg, Switzerland). In the field, this unit generally displayed its error as being between 0.1 and 2.0 ft. The locations of the GPS points were determined by a third party under instructions to identify the SMZ border as it might look from the air. Because a GPS point was taken every time the border of the SMZ changed direction, connecting these points in ArcGIS reproduced the exact SMZ polygons. The macro was then run with these polygons' 38 GIS sections and the new output widths were compared with the widths from the originally digitized polygons.

There was a significant difference between the field-derived widths and the digitized widths of the SMZs ($P < 0.001$, 37 df). Because the digitized polygons resulted in underestimated widths, the results may have underreported compliance. To adjust for this potential source of error and to derive more accurate landscape-level results, we added the mean underestimation (13.0 ft) determined from field checking to the calculated width of each digitized GIS section. The difference between the field-derived and the imagery-derived width measurements is caused by the interplay between the rectification of the FSA imagery, the resolution of the FSA imagery, and digitizing error. These factors can explain the consistent underreporting in two ways. First, rectification problems, inevitably worsened by the tendency of SMZs to be located on slopes, will be present for all imagery across the landscape. Second, the digitizer may have consistently interpreted the last gray pixels between the SMZ and the harvested land as falling outside, rather than inside, the border of the SMZ. With higher-resolution orthorectified imagery, we expect that the disparity between field-based and GIS-based measurements would largely disappear. Although we were able to statistically correct for the error on a landscape level, we found that publicly available FSA imagery would be inadequate for landowners wishing to measure the width of a particular SMZ.

Table 2. SMZ compliance results for GIS sections, whole SMZs, and tax parcels.

	Compliance threshold	BMP/SFI compliance (%)	FSC compliance (%)
GIS sections ($n = 5080$)		92.9	52.9
Whole SMZs ($n = 165$)	100%	52.1	9.1
	90%	75.8	15.2
	80%	84.2	21.2
Tax parcels ($n = 110$)	100%	50.9	13.6
	90%	79.1	20.0
	80%	87.3	22.7

Notes: The compliance of whole SMZs and tax parcels was based upon the compliance of the GIS sections they contained. The compliance threshold determines the percentage of constituent GIS sections that must be compliant for the whole SMZ or tax parcel to be considered compliant. All figures compensate for the results of width field checking by adding 13.0 ft to the width of each GIS section before evaluating compliance.

BMP/SFI and FSC Compliance

The average width and slope of the GIS sections were analyzed on several spatial scales and management levels. We used Pearson's chi-square test for all statistical tests on results data.

The simplest and most basic assessment was that of compliance by GIS section. There was a significant difference between using BMP/SFI and FSC to assess compliance ($P < 0.001$, 1 df). Over 90% of GIS sections complied with BMP/SFI, and just over 50% complied with FSC (Table 2). The average width of a GIS section was 101.8 ft (31.0 m). The widths of GIS sections exceeded the widths recommended by state BMPs/SFI by an average of 74.7 ft (22.8 m) with a median of 59.5 ft (18.1 m), and they exceeded the widths recommended by FSC by an average of 22.5 ft (6.9 m) with a median of 5.5 ft (1.7 m) (Figure 2). The majority of the GIS sections could have had their SMZ widths reduced by more than 50 ft while still complying with the quantitative SMZ standards of state BMP/SFI.

Slope had a significant effect on compliance for both BMP/SFI ($P < 0.001$, 5 df) and FSC ($P = 0.04$, 5 df). For BMP/SFI, compliance typically fell as the slope class and required width increased, but slope appeared to have a smaller effect on FSC compliance (Figure 3). BMP/SFI compliance was near 100% when a slope of less than 10% indicated a width threshold of 25 ft.

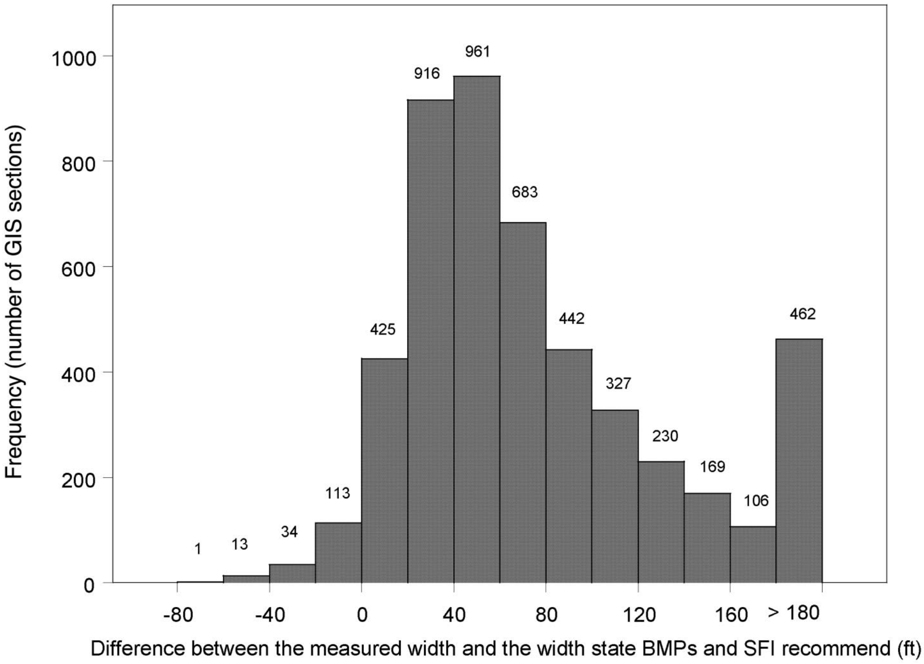
There were 198 GIS sections of blue line streams within recently harvested areas that contained no discernible SMZ. Therefore, of the 359 GIS sections that failed to comply with state BMP/SFI, more than one-half failed not because their widths were below the standard's thresholds but because they contained no SMZ at all. These GIS sections with nonexistent SMZs were spread between 45 discrete stream reaches totaling 2.2 mi (3.6 km) in length. The shortest of these reaches was 25.3 ft (7.7 m), and the longest was 1,291.7 ft (393.7 m). The average length of a reach of stream that lacked an SMZ was 263.5 ft (80.3 m).

The GIS sections also were regrouped into whole SMZs and tax parcels to assess compliance on larger spatial scales and higher management levels (Table 2). We assessed the compliance of each of these larger units by determining the percentage of its constituent GIS sections that were compliant. All compliance figures in this text use a threshold where at least 9 of 10 of the constituent GIS sections were compliant.

BMP/SFI compliance differed significantly from FSC compliance for both whole SMZs ($P < 0.001$, 1 df) and tax parcels ($P < 0.001$, 1 df). BMP/SFI compliance of whole SMZs was about 75% (Table 2). FSC compliance of whole SMZs was about 15%. The lengths of the whole SMZ centerlines ranged from 258.5 ft to 2.6 mi (78.8 m to 4.2 km), and the mean was 2,528.9 ft (770.8 m). Approximately 79% of the tax parcels complied with BMP/SFI, and 20% complied with FSC-level standards (Table 2).

We used county tax data from the year 2000 to classify tax parcels according to the type and the location of the owners (Figure 4). The "owner type" classification includes noncorporate individuals, companies with a prime interest in harvesting timber, and companies for which timber harvesting is an ancillary or incidental interest. This classification is mutually exclusive but is not exhaustive. The "owner location" classification grouped tax parcels according to a mutually exclusive, exhaustive scheme: "county" includes those parcels with owners located in the same county or in a contiguous county, "state" includes those parcels with owners from elsewhere in Tennessee, and "out of state" includes all other parcels.

Neither owner type ($P = 0.10$, 2 df) nor owner location ($P = 0.16$, 2 df) had a significant effect on BMP/SFI compliance. FSC compliance, however, was significantly affected by both owner type ($P = 0.04$, 2 df) and owner location ($P = 0.02$, 2 df). Tax parcels owned by timber companies were less FSC compliant than were those owned by individuals or nontimber companies. In addition, tax parcels with owners from outside the state were less FSC compliant than were those with owners classified as "county" or "state." The "out of state" and "timber company" categories do not entirely overlap. Although nearly all of the parcels owned by timber companies also were classified as having owners from outside the state, nearly one-half of the parcels with owners from outside the state were not owned by timber companies.



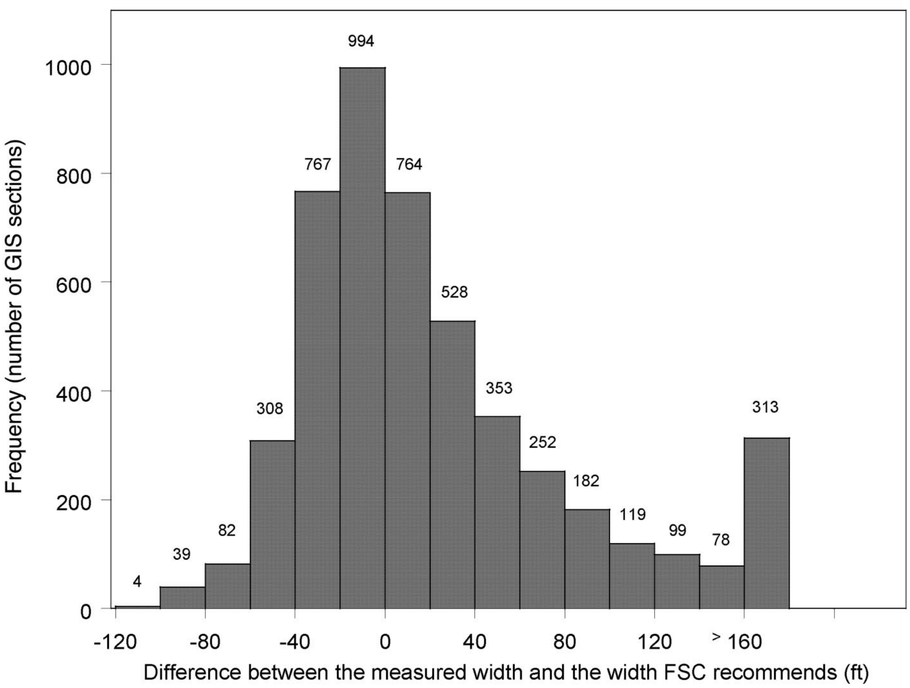


Figure 2. The difference between the measured width of GIS sections and the width that state BMPs/SFI (top) and FSC (bottom) recommend. Positive values represent width in excess of the standards and negative values represent width that a GIS section would need to gain to be compliant with the standards. The measured width has been adjusted by adding 13.0 ft, the mean error from field checking. One hundred ninety-eight GIS sections represented areas without an SMZ and therefore had no measured slope or, by extension, recommended width.

In assessing the sustainability of forestry activities, one must decide on a measure of sustainability. Because using FSC instead of state BMPs/SFI presents a rather different picture of SMZs on the southern Cumberland Plateau of Tennessee, the choice between sustainable forestry standards may have important consequences. The SMZ guidelines of FSC require greater widths than do those of the state BMPs/SFI, but none of these three standards supports its SMZ guidelines with references to scientific sources. If the SMZ standards in state BMPs/SFI are seen as adequate, then the 75.8% compliance of whole SMZs with state BMPs/SFI is encouraging; if the more demanding SMZ standards of FSC are viewed as necessary for watershed protection in this region, then the 15.2% FSC compliance of whole SMZs on the plateau is cause for concern. For the blue line SMZs created between 2000 and 2003, the widespread adoption of SFI standards or the imposition of mandatory state BMPs would likely have had little impact on SMZ widths in this landscape. The widespread adoption of FSC standards, however, would have necessitated a transformation in the design of riparian buffers on the plateau.

Evaluation of SMZ Remote Assessment

This methodology has several distinct advantages. We studied a complete landscape-level population of blue line streams without relying on sampling regimes. This GIS assessment is reproducible on a variety of spatial scales, and it avoids the labor and time requirements of measuring such a large number of SMZs in the field. Some authors (e.g., Willson and Dorcas [2003], Lee et al. [2004]) have advocated shifting the management focus away from individual stands and toward entire watersheds, but such a shift in focus requires a corresponding shift in information gathering techniques. A GIS methodology such as this can provide the accurate landscape-level information necessary to manage and monitor the landscape-level effects of large forestry operations.

A watershed study could extend this methodology by measuring the prevalence and widths of SMZs on a more detailed stream network, such as one derived from DEMs. Hansen (2001) suggests that USGS blue line streams should not be used to indicate which streams should claim BMP protections. Using only blue line streams ignores many ecologically important elements of the stream network and overemphasizes higher-order streams. For this study, restricting the focus to blue line streams pro-

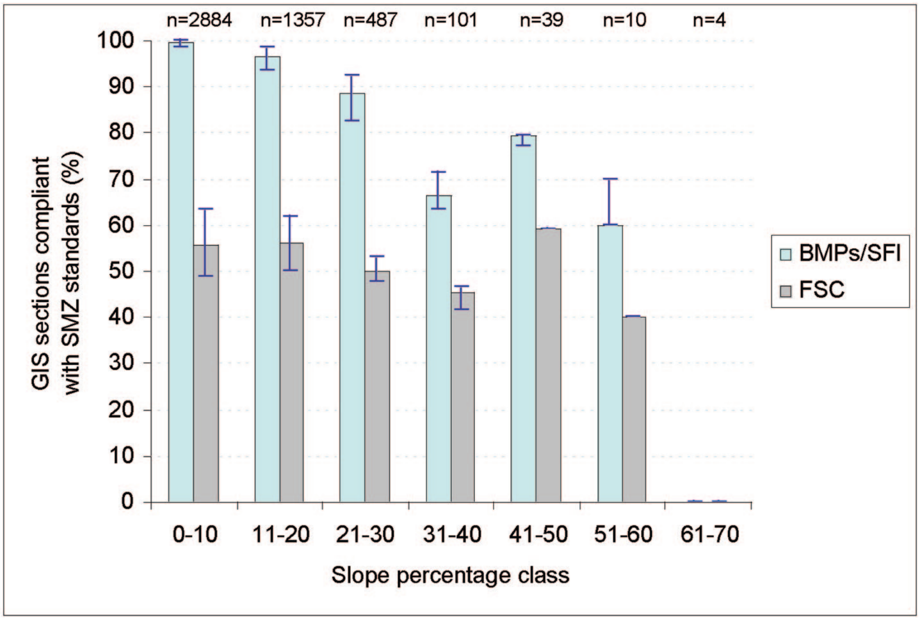


Figure 3. SMZ compliance of GIS sections by slope percentage class. Error bars represent the 95% confidence interval determined from width field checking. One hundred ninety-eight GIS sections represented areas without an SMZ and therefore had no measured slope.

vided a readily identifiable population with an indisputable claim to BMP protection. As a result, however, the compliance figures presented here are conservative because they comprise only the most prominent elements of the stream network.

As previously noted, the SMZ guidelines of FSC, SFI, and state BMPs currently are not based on a scientific consensus for what constitutes effective watershed protection in this region. SMZ recommendations in the literature depend on the specific ecological concern in focus (e.g., Wenger [1999], Kiffney et al. [2003]), and SMZ width guidelines usually are balanced against economic and practical concerns (e.g., Bren [1995]). Landscape trends matter for many ecological metrics (e.g., Keim and Schoenholtz [1999], Willson and Dorcas [2003]), and this study provides the first usable technique for precisely measuring SMZs across a landscape. By allowing SMZ data to be tested on a larger spatial scale for effects on ecological metrics, this type of GIS assessment could help to advance the debate over optimal SMZ width.

In conclusion, we feel that combining this methodology with orthorectified imagery of better resolution would provide a powerful new tool for forestry. Using FSA imagery that had not been precisely orthorectified led to an average error in SMZ width estimation of over 10% of the mean SMZ width, but we expect that improved imagery would substantially reduce this error. A GIS analysis could supplement state-sponsored BMP surveys, which in Tennessee have yet to study conclusively the compliance of SMZs (Prud'homme and Greis 2002). It also could be used to improve studies that examine BMP compliance in states with different regulatory regimes (e.g., Floyd and MacLeod [1993]), and the SMZs in FSC- and SFI-certified forestry operations could be compared to assess the effects of the standards on forestry practices. Most importantly, watershed-level SMZ data could be correlated with water quality data and ecological metrics, which may enable the development of models that could be used to predict the effects of new or proposed harvesting activity on regional water quality and ecology.

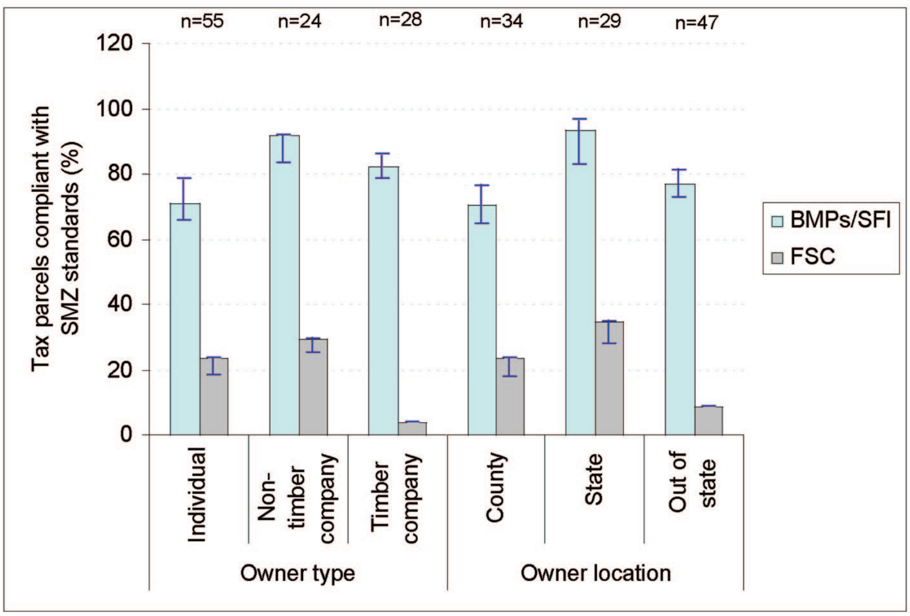


Figure 4. SMZ compliance of 110 tax parcels classified by owner type and owner location. Error bars represent the 95% confidence interval determined from width field checking. A tax parcel was considered compliant if at least 90% of its GIS sections were compliant.

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