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Estimating Annualized Riparian Buffer Costs for the Harpeth River Watershed

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Water pollution from nonpoint sources is increasingly a focal point for efforts to reduce water quality impairments. These efforts often require or subsidize riparian buffer strips. However, the costs of these buffer strips are not always well understood. This article estimates the annualized costs of establishing and maintaining 45.7-meter (150-feet) riparian buffer strips on all agricultural land adjoining a waterway in Tennessee's Harpeth River watershed. A mandatory requirement for buffer strips of this width would result in 4,955 hectares (12,245 acres) of buffer strips at an annualized cost of $1.3 million. A supply curve for buffer strips is also constructed.

Since the passage of the Clean Water Act (CWA), largely unregulated nonpoint sources (NPS) of pollution have contributed to an increasing share of the nation's water quality problems (Copeland). While the amount of agricultural land in the United States has remained relatively constant over the past thirty years, agricultural production has increased because of technological advances and increasingly fertilizer-intensive agricultural practices. These fertilizer-intensive practices have been a major contributor to a threefold increase in the nitrate load in the Mississippi River entering the Gulf of Mexico (Greenhalgh and Sauer). When the states and territories surveyed the nation's rivers and streams, they found 39% of the segments surveyed impaired for one or more uses. Agriculture was listed as a contributor to 48% of these impairments—more than twice as much as any other source (USEPA 2002).

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Reducing environmental externalities associated with agriculture poses a number of difficult policy challenges. In the context of water quality, NPS runoff from agricultural lands has proven to be relatively resistant to regulation. For example, the CWA imposes effluent limitations on point sources but not on NPS and explicitly exempts "agricultural stormwater discharges" from the definition of point sources (Houck).[1] The void created by the absence of federal regulation has been filled with a variety of voluntary programs (Houck). More recently, it has been filled by the promotion of policies that would allow point sources subject to the CWA's effluent limitations to satisfy some of these restrictions by leasing effluent reductions from NPS. This has come to be known as "water quality trading" (USEPA 2003b, 1996). States, attracted by the possibility of reducing pollution abatement costs, have implemented a number of water quality trading (WQT) programs (Breetz et al.).

States have also stepped into the void by enacting statutes that address NPS pollution by requiring landowners to observe mandatory "setback" or "buffer" requirements along waterways. These statutes tend to be limited in their application to specific activities or waterways, or both. For example, while the Georgia Erosion and Sedimentation Control Act prohibits land-disturbing activities within 7.6 meters (25 feet) of the banks of any state water, it exempts a fairly extensive list of activities from the prohibition, including "agricultural practices, forestry land management practices, dairy operations, livestock and poultry management practices, construction of farm buildings. . ." (Georgia Department of Natural Resources). North Carolina has adopted regulations designed to protect a 15.2-meter (50-feet) riparian buffer along waterways in the Neuse and Tar-Pamlico River Basins (North Carolina Department of Environment and Natural Resources). Virginia's Chesapeake Bay Preservation Act provides for 30.4-meter (100-feet) buffer areas along specifically designated "Resource Protection Areas," but allows encroachments into buffer areas for agricultural and silvicultural activities under certain conditions (Chesapeake Bay Local Assistance Board).

Riparian buffer strips—areas of trees, shrubs, or other vegetation along surface water bodies—have also played a prominent role in federal and state voluntary programs to reduce NPS pollution. For example, the Conservation Reserve Program has supported the use of buffer strips since 1988 (Prato and Shi) and funds made available to states through the CWA's Section 319 program are often used to subsidize buffer strip installation (Nakao and Sohngen). Buffer strips are proving an attractive policy option because of their effectiveness in intercepting and removing nutrients, sediment, organic matter, and other pollutants before these pollutants enter surface water and because of the other environmental benefits they provide, including improved terrestrial and aquatic habitat, flood control, stream bank stabilization, and esthetics (Qiu, Prato, and Boehm).

NPS pollution has typically avoided the type of regulation imposed on point sources. However, its prominent role in the impairment of surface and ground water quality means that water quality cannot be meaningfully improved without addressing agricultural NPS pollutant loadings. The possibility that the costs of abating pollution from NPS are lower than costs of abating pollution from point sources (Faeth) may also make NPS an attractive target. In any event, buffer strips are proving to be a relatively popular means of controlling NPS discharges. Although agriculture has often been excluded from regulation, there is no

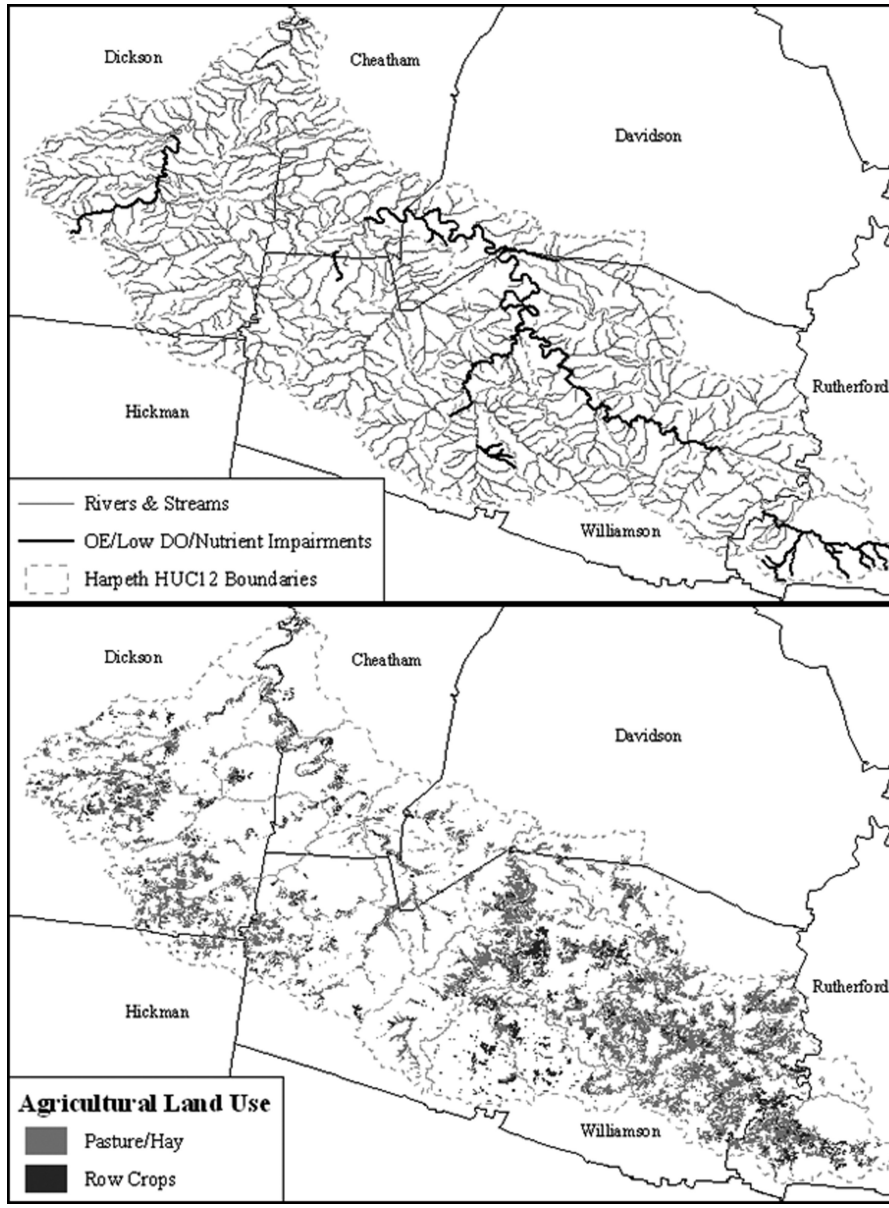
guarantee that the agricultural sector will continue to enjoy this treatment. For example, North Carolina's Department of Water Quality drafted, but did not adopt, regulations that would have required all crop farms adjacent to streams to install buffer strips (Schwabe). In the absence of regulation of agricultural NPS, it seems likely that alternatives to regulation will continue, if not increase. Many of these will promote the installation of buffer strips through subsidies of one form or another. For example, the Conservation Reserve Enhancement Program, which subsidizes conservation-oriented practices by landowners, has established a goal of installing 157,000 miles of riparian buffers, filter strips, and wetlands in states in the Chesapeake Bay watershed (Bonham, Bosch, and Pease).

However, it has been suggested that the costs associated with riparian buffers are often not known with any certainty (e.g., Ice, Skaugset, and Simmons). Thus, this article is an attempt to quantify the annualized costs of installing and maintaining vegetative buffer areas of approximately 45.7 meters (150 feet) between agricultural production activities and riparian features in Tennessee's Harpeth River watershed (figure 1). The 45.7-meter (150-feet) buffer width was chosen, in part, on the basis of a meta-analysis conducted by Mayer et al., that found that buffer strips less than 50 meters (164 feet) displayed considerable variation in effectiveness in removing nitrogen, while nearly all buffers in excess of 50 meters (164 feet) would achieve at least a 75% removal effectiveness. In addition, the greater width helped to ameliorate some of the difficulties associated with the relatively course resolution of the underlying data. Clearly, the choice of buffer strip width has a profound impact on the costs associated with the buffer and 45.7-meter (150-feet) buffers easily exceed most, if not all, existing buffer strip requirements or recommendations. While an analysis of the relationship between costs and buffer width would undoubtedly be valuable, the validity of such an analysis would depend upon the spatial resolution of the data used.

These costs are used to estimate the annualized costs that a regulation requiring all agricultural producers to install and maintain such buffer areas would impose on agricultural producers in the watershed. The costs are also used to estimate a supply curve of vegetative buffer strips, which may be of interest to policy makers considering the adoption of WQT programs, since the supply of riparian buffer strips will bear some proportional relationship to the supply of agricultural NPS effluent reduction credits. Individual buffer strips, however, will have different pollutant load-reduction impacts based on current farmer practices, soil types, and proximity to water quality impairments, among other factors. While the unique environmental impacts of each buffer strip are not considered in this article, the differential impacts of soil type and current land use on the value of each potential riparian buffer strip are explicitly considered in estimating the annualized costs of these buffer strips. This approach to estimating the costs of buffer strips differs somewhat from previous economic analyses of buffer strips and may be of use to water quality program administrators as it relies solely on publicly available data and relatively straightforward procedures.

The remainder of the article is structured as follows. A review of literature on the economic analysis of vegetative buffer strips is presented first. This literature review is followed by a brief overview of the Harpeth River watershed. The methods and procedures used to identify the location of buffer strips and to estimate the annualized costs of these buffer strips are then described in some detail.

Figure 1. The Harpeth river watershed in Tennessee



A discussion of the results of these processes follows. Finally, some concluding thoughts are offered.

Literature Review

The literature analyzing the effectiveness of riparian buffer strips in preventing pollutants from entering nearby surface water is expansive (e.g., Burkart, James, and Tomer; Lowrance, Dabney, and Schultz; Lynch, Hardie, and Parker; Nakao

and Sohngen). A general characterization of this literature is that, while buffer strips can be highly effective, their effects are also highly site specific (Polyakov, Fares, and Ryder; Tomer, James, and Isenhart). Thus, there are potentially large benefits to targeting buffer strip installation to those circumstances in which they can be most effective (Burkart, James, and Tomer; Dosskey, Helmers, and Eisenhauer; Norris; Polyakov, Fares, and Ryder; Tomer, James, and Isenhart; Yang and Weersink) and to conforming buffer strip design to local environmental conditions (Dosskey, Eisenhauer, and Helmers). Of course, the costs of buffer strips, in particular the opportunity cost or value of alternative uses of the land, are also highly variable from one location to another.

The extent and ways in which this cost variability has been included in economic analyses of buffer strips have varied widely. For example, Epp and Hamlett evaluated eight different best management practices (BMPs), including buffer strips, at the individual field level across three sites that differed in terms of soils, field conditions, and types of farming operations. Jacobs and Timmons optimized the distribution of agricultural land uses (including conservation practices) over different soil types in a single watershed to find the least-cost means of achieving water quality targets. They estimated the cost of permanent pasture (they did not explicitly consider buffer strips) as the difference in net returns between pasture and a corn-corn-soybean rotation. Frimpong, Lee, and Sutton included land rental, establishment, and maintenance costs, estimating land rental values through a spatial analysis of quarterly land transactions data for a sixteen-county region and capturing variation in land values by modifying median values based on the likelihood of flooding. Schwabe estimated costs in terms of lost row crop production and treated individual counties as multiproduct farms growing corn, cotton, and soybeans and incorporated county-level variation in average crop yield and production costs. Bonham, Bosch, and Pease estimated buffer strip costs using a mathematical programming model to estimate the decrease in farm profits associated with buffer strips, explicitly considering the effect on these cost estimates of alternative spatial representations of farms. In estimating the land opportunity costs of reducing soil erosion with buffer strips (in addition to installation and maintenance costs), Nakao and Sohngen employed a hedonic analysis to value different soil types, but suggested that soil productivity indices and crop budgets could be used in a similar fashion.

Prato and Shi and Qui and Prato (1998, 2001) use the reduction in total watershed net return as the cost basis for estimating the cost-effectiveness of buffer strips. Pritchard, Lee, and Engel estimated farm and government costs of vegetative filter strips, assuming that farm costs were equal to the loss in net return from land placed in filter strips while government costs were equal to the maximum acceptable rental rate. Kramer et al. used uniform per-acre opportunity, installation, and maintenance costs in a simulation model analyzing buffer strip cost-effectiveness. Stonehouse estimated the farm-level impacts of adopting a buffer strip by estimating productivity changes due to changes in production practices and soil productivity. Rickerl, Janssen, and Woodland considered government subsidies in estimating net returns to buffer strips. Qiu, Prato, and Boehm used contingent valuation and hedonic pricing to estimate the value of buffer strips, open space and farmland preservation. Henri and Johnson evaluated the effect of different management practices on the income potential of a forested buffer strip. Examples of economic analyses of forested buffer strips can be found in Countryman and Murrow; LeDoux; and Li, LeDoux, and Wang.

Table 1. Source and location of data used in analysis

Data	Source	Location
Land use	1992 NLCD	http://landcover.usgs.gov/natllandcover.php
Waterways	NHD	http://nhd.usgs.gov/index.html
Soil	STASGO	http://www.soils.usda.gov/survey/geography/statsgo/
Crop yield	STASGO	http://www.soils.usda.gov/survey/geography/statsgo/
Crop area	QuickStats	http://www.nass.usda.gov/Data_and_Statistics/Quick_Stats/
Crop budgets	UT Extension	http://economics.ag.utk.edu/budgets.html

This article illustrates the use of soil productivity and crop budgets in calculating annualized buffer strip costs for individual agricultural parcels within Tennessee's Harpeth Valley watershed. Thus, one benefit of the approach utilized in this article is that it captures variation in land value at the individual parcel level using publicly available data in a process that could be easily replicated by the administrators of water quality programs.

Materials and Methods

Overview of Project Area

The Harpeth River watershed is located to the west and southwest of Nashville in Middle Tennessee, encompassing parts of Cheatham, Davidson, Dickson, and Williamson Counties (figure 1). The watershed drains 224,552 hectares (867 square miles) through approximately 2,195 kilometers (1,364 miles) of streams before emptying into the Cumberland River (USEPA 2004). The most recent land use data for the watershed at the time of analysis was from the 1990 to 1993 MultiResolution Land Characteristic Consortium in the form of the 1992 National Land Cover Database (NLCD) (table 1).[2] At that time, 24.2% or 72,574 hectares (179,335 acres) of the watershed were in agricultural use. Pasture/hay accounted for 52,728 hectares (130,294 acres), while row crops covered the remainder. The Harpeth River watershed was chosen for this research because it has streams that are impaired due to "Organic Enrichment/Low Dissolved Oxygen," is predominantly rural, and is the only watershed in the state of Tennessee with a finalized total maximum daily load of pollutants (TMDL) for this nutrient-related impairment. The TMDL provides specific targets for NPS nutrient reduction needed in the watershed. In this case, it calls for a 65% reduction in the sediment oxygen demand (i.e., the rate of oxygen consumption exerted by the bottom sediment on overlying water) from NPS pollution in the upper Harpeth River. It also calls for anywhere from a 20% to 53% reduction in nitrogen loadings from NPS in the various subwatersheds of the lower Harpeth River watershed (USEPA 2004).

Geographically Locating Buffer Strips

Agricultural land uses were isolated from other land uses in the watershed using the 1992 NLCD and ESRI's ArcGIS software (ESRI). The NLCD shows two classifications of agricultural land use in the watershed, namely "row crops" and

"pasture/hay." Once these lands were located and isolated, they were geospatially attached to riparian features based on proximity as shown in the U.S. Geological Service's National Hydrography Dataset (table 1). This process was accomplished by creating a 45.7-meter (150-feet) buffer in ArcGIS around all riparian features, and then attaching the land use features to this buffer. The area of the agricultural land within the buffer area was then calculated using ArcGIS. This area represented the land that would be used in riparian buffers under a potential regulatory program.

Calculating Annualized Buffer Strip Costs

Riparian buffer strips generate establishment, maintenance, and land opportunity costs (Bonham, Bosch, and Pease; Purvis et al.). While buffer strips may generate other difficult-to-estimate costs associated with such factors as increased predation from wildlife and increased equipment maneuvering (Lynch and Brown), we have not attempted to include these costs, in large part due to their idiosyncratic nature. We also assume that no financial benefits accrue to the owners of the property on which the buffer strips are located even though there would be a financial benefit if grass or trees were harvested from the strip. The timing of these costs (and benefits) must also be considered (Nakao and Songen). Establishment costs occur at the time of strip establishment while maintenance and opportunity costs occur on a recurring basis. To calculate an annual aggregate cost, establishment costs are annualized over the expected life of the buffer strip and added to annual maintenance and opportunity costs.

Cropland Opportunity Costs

Cropland was valued at its opportunity cost, which was determined based on cropping practices and soil fertility, assuming that crop area in the watershed is distributed as in the overlying counties. The most recent county crop area data, available from the U.S. Department of Agriculture (table 1), were used to estimate the cropland use in each county. Corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and soybeans (*Glycine max* L.) are the major row crops planted in the Harpeth River watershed, so cropland buffer is assumed to be a county-weighted average of corn, soybean, and cotton crops.[3] While there is some possibility that winter wheat (*Triticum aestivum* L.) was also grown on the row crop land that would be converted to buffer strips, it is unlikely that this wheat would contribute much, if at all, to producer returns. A relatively small proportion of the wheat grown in this area has traditionally been harvested, as much of it has been grown as a cover crop. Obviously, an increase in the price of wheat could lead to an increase in wheat harvested, and possibly even, planted. Given past practices, potential revenues from the sale of winter wheat are not included in this analysis even though there may be some instances in which producers are able to generate such revenues from the areas that would be converted to a buffer strip. The most current area data available were for 2004; however, the most recent soybean area data available for Davidson and Dickson counties were for 2001 and 2002, respectively. Corn silage area data were from the 2002 Census of Agriculture (USDA 2004b). Corn grown for silage presents a problem as it is not typically transacted on a market but is often grown locally as a feed by livestock producers. Thus, reducing the amount of corn silage will increase the costs of these operations in ways that are difficult to measure. However, as these counties produce relatively little corn

silage, corn area was assumed to be the sum of corn area for grain and silage from the aforementioned sources.

The State Soil Geographic (STATSGO) Database (table 1), served as a measure of soil fertility. The STATSGO database is compiled by generalizing the more detailed Soil Survey Geographic (SSURGO) Database (USDA 1994). Although the relatively course spatial resolution of the STATSGO data is not ideal for this application, the SSURGO data for the area had not been digitized at the time of the analysis. In any event, the STATSGO data set divides the area into mapping units, or areas with similar soil patterns and soil type compositions. It also provides the proportions of each mapping unit by soil type. Furthermore, the data provide estimated per-acre yields for each crop and soil type combination. A weighted-average yield was obtained for each crop and mapping unit by multiplying the yield for a given soil type by the soil's proportion within the mapping unit divided by the sum of the proportions of all soil types where the crop was grown, then summing these products for each crop. The above process is summarized as

$$\text{¥}_{ij} = \sum_{k=1}^{n} \left(\frac{Y_{ik} P_{jk}}{\sum_{j=1}^{m} P_{jk}} \right) \tag{1}$$

where ¥_{ij} is the weighted-average yield for crop i in mapping unit j, Y_{ik} is the STATSGO yield for crop i on soil type k, P_{jk} is the proportion of soil type k in mapping unit j, m is the total number of soil types on which crop i is grown in mapping unit j, and n is the total number of soil types in mapping unit j. Division by the denominator is necessary because crops are not grown on all soil types within a mapping unit (e.g., corn does not grow on rock outcrop).

These weighted-average yields for each mapping unit were 1994 yields, consistent with the STATSGO database. They were inflated to 2004 yields to reflect advances in production technology and the interaction of these advances with changes in the resource base in each county. The yield inflator was the ratio of the expected 2004 yield to the expected 1994 yield for each county and crop. Expected yields were used to mitigate the effects of weather, disease, and other factors that might cause annual variation in yields from sources other than advances in technology and changes in the resource base. A yield inflator was created for each crop in each county to account for the possibility that agricultural production might be relegated to land that is more (or less) productive in rapidly urbanizing counties, as compared with a rural county in which land use remains largely unchanged over time. Expected yields for each crop in each county were found by regressing yield on a time trend from 1987 through 2004 (table 2) and using the resulting equations to predict yields in 1994 and 2004. For corn in all counties, the time variable had a statistically significant and positive effect on yield at the 0.05 level or better, as is also the case for cotton crops. Effects of time on soybean yields were only significant for Hickman and Rutherford Counties. The yield inflator for crop i in county f was calculated as $I_{if} = \hat{y}_{if2004} / \hat{y}_{if1994}$, where $\hat{y}_{if2004}$ and $\hat{y}_{if1994}$ are yields predicted from the trend regressions for crop i in county f (table 2). The 2004 weighted-average yields were calculated as

$$\tilde{Y}_{ifj} = I_{if} \text{¥}_{ij} \tag{2}$$

Table 2. Estimated trend regressions and yield inflators by crop and county

County	Crop	Equation	R^2	Yield Inflator (I_{if})
Cheatham	Corn	$\hat{y}_{ift} = \underset{(6.67)}{62.52} + \underset{(0.62)}{3.43}t$	0.66	1.38
Davidson	Corn	$\hat{y}_{ift} = \underset{(6.62)}{66.19} + \underset{(0.78)}{2.50}t$	0.56	1.29
Dickson	Corn	$\hat{y}_{ift} = \underset{(7.94)}{62.74} + \underset{(0.73)}{2.81}t$	0.48	1.33
Hickman	Corn	$\hat{y}_{ift} = \underset{(7.91)}{81.33} + \underset{(0.73)}{1.70}t$	0.25	1.18
Rutherford	Corn	$\hat{y}_{ift} = \underset{(7.77)}{61.43} + \underset{(0.72)}{3.11}t$	0.54	1.36
Williamson	Corn	$\hat{y}_{ift} = \underset{(8.17)}{73.98} + \underset{(0.76)}{2.90}t$	0.48	1.30
Cheatham	Soybeans	$\hat{y}_{ift} = \underset{(2.92)}{28.95} + \underset{(0.27)}{0.42}t$	0.14	1.13
Davidson	Soybeans	$\hat{y}_{ift} = \underset{(2.71)}{27.43} - \underset{(0.35)}{0.14}t$	0.02	0.95
Dickson	Soybeans	$\hat{y}_{ift} = \underset{(3.79)}{23.56} + \underset{(0.34)}{0.39}t$	0.12	1.15
Hickman	Soybeans	$\hat{y}_{ift} = \underset{(2.81)}{23.61} + \underset{(0.26)}{0.70}t$	0.31	1.24
Rutherford	Soybeans	$\hat{y}_{ift} = \underset{(3.14)}{21.34} + \underset{(0.29)}{0.80}t$	0.31	1.28
Williamson	Soybeans	$\hat{y}_{ift} = \underset{(3.28)}{25.35} + \underset{(0.30)}{0.58}t$	0.18	1.19
Rutherford	Cotton	$\hat{y}_{ift} = \underset{(51.21)}{367.29} + \underset{(4.73)}{18.57}t$	0.49	1.36

[a]Numbers in parentheses are standard errors.

where $\tilde{Y}_{ifj}$ is the 2004 weighted-average yield for crop i in mapping unit j in county f, I_{if} is the yield inflator for crop i in county f, and $\bar{Y}_{ij}$ is the 1994 weighted-average yield for crop i in soil mapping unit j.

Crop budgets developed by University of Tennessee Extension (University of Tennessee Extension) were consulted to determine the returns to land, management, and risk for different crop yields. Net returns were assumed linearly or piecewise linearly related to expected yield. Piecewise linear functions were used for crops with budgets with more than one yield goal. For example, corn budgets were available for yield goals of 7,532 and 9,415 kg per hectare (120 and 150 bushels per acre). Returns were estimated by linear interpolation between the returns at each yield goal, assuming a zero return for an expected yield of zero.[4] The interpolation equations were

$$\Phi_{ifj} = \begin{cases} 0.4523\tilde{Y}_{ifj} & \text{if } Y_{ifj} < 120 \\ 1.21\tilde{Y}_{ifj} - 80.24 & \text{otherwise} \end{cases} \quad \text{for } i = \text{corn} \tag{3}$$

$$\Phi_{ifj} = 1.5945\tilde{Y}_{ifj} \quad \text{for } i = \text{soybeans and} \tag{4}$$

$$\Phi_{ifj} = 0.034621\tilde{Y}_{ifj} \quad \text{for } i = \text{cotton} \tag{5}$$

Table 3. Crop proportions by county

County	Corn (%)	Soybeans (%)	Cotton (%)
Cheatham	29	71	0
Davidson	52	48	0
Dickson	67	33	0
Hickman	41	59	0
Rutherford	34	51	15
Williamson	36	64	0

where Φ_{ifj} is the 2004 weighted-average return to land, management, and risk for crop i on mapping unit j in county f, and $\tilde{Y}_{ifj}$ is the 2004 weighted-average yield for crop i in county f in mapping unit j. The slopes for these linear equations are simply the slope of a ray from the origin through the net return/yield combination derived from the crop budgets, or in the case of corn yielding more than 7,532 kg per hectare (120 bushels per acre), the slope of the line between the net return/yield combination for corn yielding 7,532 kg per hectare (120 bushels per acre) and corn yielding 9,415 kg per hectare (150 bushels per acre).

A weighted-average net return per hectare was calculated for each buffer strip as

$$\Pi_{fj} = \sum_{i=1}^{n} E_{if}\,\Phi_{ifj} \tag{6}$$

where Π_{fj} is the weighted-average return per hectare for mapping unit j in county f, E_{if} is the proportion of land in crop i in county f, Φ_{ifj} is the 2004 weighted-average return to land, management, and risk from crop i in county f on mapping unit j, and n is the total number of crops grown in county f.

County crop proportions used to develop these weighted-average returns per hectare are presented in table 3. The per-hectare returns are the expected returns that producers would forego by establishing a buffer strip on the land (opportunity cost). Note that the figures in table 3 assume homogeneous yields and costs throughout the mapping unit surrounding the buffer. There is reason to believe, however, that this assumption is not entirely accurate. For example, soil near a stream bed is likely to have distinct properties from soil in the rest of a field with regard to moisture content, particle size, and slope, which are likely to affect yield potential, as well as cultivation costs. Yet, our assumption simplifies the task at hand by allowing the use of publicly available data.

Pasture Opportunity and Exclusion Costs

Agricultural land classified by the 1992 NLCD as "pasture/hay" was assumed to be pasture land, since about 70% of hay in Tennessee is grown for on-farm use in livestock operations, implying that many hayfields may occasionally be used rotationally as pasture by livestock producers (USDA 1996). Such being the

case, fencing for stream exclusion of livestock would be required for all land designated "pasture/hay." This assumption may cause an overestimation of the cost of a vegetative buffer strip on such land, because not all hay fields are likely to enter a grazing rotation.

The average reported cost of exclusion fencing (USEPA 2003a), adjusted for inflation using the index of prices paid by farmers was $366.67 per kilometer. Each potential pasture buffer polygon (multisided area) has a perimeter in the ArcGIS attribute table, which was used to calculate the required livestock exclusion fencing for each polygon. Fencing requirements were calculated as

(7)
$$F_l = B_l - 4 * 0.0457 \quad \text{if pasture is present on both sides of the water body, and}$$

(8)
$$F_l = \frac{(B_l - 2 * 0.0457)}{2} \quad \text{if pasture is present on only one side of the water body}$$

where F_l is the number of kilometers of fence required for buffer strip l, B_l is the perimeter of buffer feature l in kilometers, and 0.0457 is the width of the buffer strip in kilometers. Note that if pasture is present on both sides of a water body—as in equation (7)—a buffer zone is required on both sides of the stream, necessitating fencing along the length of each of the buffers for cattle exclusion. If as in equation (8), pasture is present only on one side of the stream, only one buffer is required, and fencing is required only along the length of that buffer (hence, we divide the buffer length by 2). Both equations (7) and (8) exempt the width of the buffer zones from fencing (by subtracting four and two times the buffer width from fencing requirements, respectively) because we assume that pasture is already fenced off from adjacent land uses.

Exclusion costs for some pasture features within the buffer area were negative because their perimeters were less than 91.4 meters (300 feet) for features on one side of a stream or less than 182.9 meters (600 feet) for features straddling a stream. Features with negative exclusion costs were assumed to be land use classification errors in the 1992 NLCD, and were excluded from cost calculations. Excluding these pasture features should have little effect on the results because each of these areas was less than 0.04 hectare (0.1 acre), and those that were not errors are likely to be cattle crossings or stream accesses for controlled watering, which could appropriately be permitted by a buffer regulation.

A per-hectare livestock exclusion cost for each potential buffer strip was calculated as

(9)
$$E_l = \frac{\$366.67 F_l}{H_l}$$

where E_l is the adjusted per-hectare exclusion cost for buffer feature l, F_l is the kilometers of fencing required for feature l, $366.67 is the adjusted per-kilometer cost of permanent exclusion fencing, and H_l is the area of buffer feature l in hectares.

The opportunity cost of a hectare of pasture was assumed to be the average rental rate for pasture, since the average rental rate should represent the average expected return to land, management, and risk for the land owner. The 2004 average cash rental rate for pasture in Tennessee was \$46.95 per hectare (\$19 per acre) (USDA, 2004a). No attempt was made to account for varying soil fertilities among pasture lands because the proportion of land in different forage crops was unknown, and the average rental rate was deemed sufficient to represent the opportunity cost of converting pasture to riparian buffers.

Total Annualized Buffer Costs

The annual maintenance costs and establishment costs annualized over the expected life of the vegetation (ten years) was assumed to be \$81.03 per hectare (\$32.79 per acre) based on the available literature (Bonham, Bosch, and Pease). Thus, the total per-hectare cost of each buffer strip was calculated as

$$C_l = \Pi_{fj} + \$81.03 \quad \text{for cropland buffers and} \tag{10}$$

$$C_l = \$46.95 + E_l + \$81.03 \quad \text{for pasture buffers} \tag{11}$$

where C_l is the total per-hectare cost of buffer strip l, Π_{fj} is the 2004 weighted-average return per hectare from cropland in county f, in mapping unit j, that contains buffer feature l, \$46.95 (\$19.00) is the expected return per hectare (acre) from the pasture land (the pasture rental rate), E_l is the per-hectare exclusion cost for pasture buffer l, and \$81.03 per hectare (\$32.79 per acre) is the annualized establishment cost plus the annual maintenance cost.

Aggregating the Annualized Costs to the Watershed Level

The estimated total cost of a mandatory regulation requiring the installation of 45.7-meters (150-feet) buffer strips on all agricultural land bordering streams in the Harpeth River watershed was calculated as

$$T = \sum_{l=1}^{n} C_l * H_l \tag{12}$$

where T is the total cost of mandatory 45.7-meter (150-feet) riparian buffer strips on all agricultural land, C_l is the per-hectare cost of buffer feature l, H_l is the area of buffer strip l in hectares, and n is the total number of potential buffer strips in the Harpeth River watershed.

Of some interest to conservation program managers or advocates of tradable emissions permits is the estimation of a supply curve for buffer strip area, since available buffers bear some relationship (dependent on proximity and contribution to stream impairments, current farmer practices, land topology, stream flow, etc.) to available pollutant load reduction. A supply curve for buffer strips was estimated by summing the area of all potential 45.7-meter (150-feet) buffer strips that would be supplied at various prices, assuming that the price equals the cost

Table 4. Summary of estimated yields and net returns by row crop

	Yield (Kg/Ha)			Net Return ($/Ha)		
Land Use	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**
Corn	7,662	5,209	9,917	163.16	93.41	272.90
Soybean	2,823	2,085	3,498	165.52	128.42	205.25
Cotton	924	719	1,164	70.54	54.91	88.91

of an additional hectare of buffer (price equals marginal cost). The supply curve was estimated as

$$S_p = \sum_{l=1}^{o} H_l \tag{13}$$

where S_p is the sum of the areas of all 45.7-meter (150-feet) buffer strips supplied at price p, H_l is the area of buffer strip l in hectares, and o is the total number of buffer strips for which $C_l \leq p$. This calculation was performed for $12.35 per hectare ($5 per acre) increments of p between the lowest and the highest C_l to obtain a series of points on the supply schedule. Linearity was assumed between consecutive points on the supply curve to calculate producer surplus, or the area below the price and above the supply curve representing the economic benefits accruing to landowners from the sale of buffers.

Results and Discussion

In the Harpeth River watershed, 4,955 hectares (12,245 acres) or 8% of the agricultural land would be consumed by a regulation requiring 45.7 meter (150-feet) riparian buffer strips on all agricultural land throughout the watershed. Of this potential agricultural buffer land, 3,506 hectares (8,663 acres) are classified as pasture/hay by the land use data and the balance of the land or 1,595 hectares (3,942 acres) are classified as row crops. A summary of the estimated yields and net returns for potential row crop buffers is presented in table 4. The weighted-average net returns per hectare for each mapping unit in each county, which represent the opportunity cost of the buffer strips, are reported in table 5. After adding annualized establishment and annual maintenance costs, the total annual costs of cropland riparian buffers range from $192.54 to $291.26 per hectare ($77.92 to $117.87 per acre), with a mean of $243.40 per hectare ($98.50 per acre). Total annualized costs of pasture buffers, including opportunity, annualized establishment, annual maintenance, and livestock exclusion costs range from $128.03 to $867.34 per hectare ($51.81 to $351 per acre), with a mean of $276.68 per hectare ($111.97 per acre). Thus, pasture buffers would cost 13% more than cropland buffers on average as livestock exclusion expenses are more than enough to offset the greater opportunity costs associated with cropland acres.

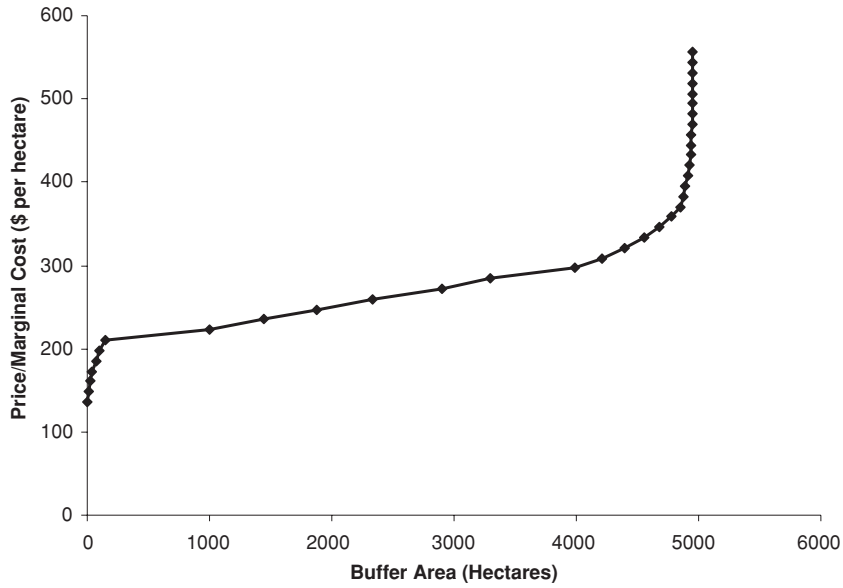
The total cost of a regulation requiring 45.7-meter (150-feet) grassed riparian buffer strips on the stream edges of all agricultural fields in the Harpeth River

Table 5. Weighted-average return to land, management, and risk for cropland

County	Mapping Unit	Buffer Strip Area (Ha)	Return ($/Ha)
Cheatham	TN054	29.1	148.39
Cheatham	TN064	13.8	207.69
Cheatham	TN073	70	137.14
Davidson	TN054	1.6	126.79
Davidson	TN064	40.9	198.52
Davidson	TN069	2.8	131.66
Davidson	TN071	2.4	177.3
Davidson	TN072	2	128.32
Dickson	TN048	10.5	141.84
Dickson	TN054	78.1	137.66
Dickson	TN060	262.6	132.67
Dickson	TN073	14.6	129.85
Hickman	TN060	16.6	220.69
Rutherford	TN054	0.4	147.3
Rutherford	TN062	34	140.6
Rutherford	TN064	17.8	208.11
Rutherford	TN067	10.1	136.7
Rutherford	TN076	93.5	129.63
Williamson	TN054	37.6	149.4
Williamson	TN060	87.8	142.36
Williamson	TN062	48.2	142.11
Williamson	TN064	354.9	210.24
Williamson	TN066	17.8	160.35
Williamson	TN067	132.7	137.71
Williamson	TN069	68.8	164.77
Williamson	TN071	146.5	187.58

watershed was estimated at $1,318,695 annually. This cost burden would be distributed unevenly among agricultural producers and would depend on the number of kilometers of water bodies abutting a producer's agricultural fields as well as the crop/pasture composition of the land and soil fertility variation. Producers could be compensated for these costs through subsidies although the annual payment required would depend upon the nature of the program. Subsidy payments tailored to individual producer costs (including opportunity cost) could keep payments low, but would likely present political difficulties and a high information burden on the regulatory agency. On the other hand, a voluntary system in which producers bid their hectares into the program could help to tailor payments to producer costs but would engender uncertainty about the number and location of producers and hectares participating in the program. Such a voluntary program would also allow a regulatory agency to account for the relative effectiveness of each buffer strip in reducing pollutant loads in impaired stream segments based on site-specific factors before choosing which bids to accept.

Figure 2. Buffer supply curve for the Harpeth river watershed



The supply curve for land in buffer strips in the Harpeth River watershed of Tennessee is shown in figure 2. If society wanted to purchase full implementation of buffer strips on the stream edges of all agricultural fields with a uniform per-hectare subsidy, the minimum subsidy required to do so would be $877.22 per hectare ($355 per acre), total payment to agricultural producers would be approximately $4,347,195, and the buffer suppliers (agricultural producers) would collectively receive $3,028,500 in producer surplus. On the other hand, because 97.9% of the buffer area is available for a cost at or below $370.66 per hectare ($150 per acre), society could achieve almost the same level of implementation at a much lower total cost, since the supply curve is nearly vertical when about 4,852 hectares (11,990 acres) of buffer strips have been purchased. The total cost to agricultural producers of installing buffer strips on these 4,852 hectares (11,990 acres), representing a 97.9% implementation rate, would be $1,276,200. This level of voluntary implementation would require a payment of $370.66 per hectare ($150 per acre), for a total subsidy of $1,798,850, providing buffer suppliers a producer surplus of $522,650. One key assumption leading to these figures is that producers have perfect knowledge concerning their profitability, but such is not likely to be the case. Many studies indicate that producers are overly optimistic regarding yields and profits (e.g., Kenyon), so the supply curve should be interpreted as the minimum cost of annual incentive payments to achieve a desired level of buffer strip implementation.

Summary and Conclusions

This study has presented methods and procedures for developing a supply curve for agricultural riparian buffer strips, which have the potential to greatly

reduce nutrient content in agricultural runoff. This supply curve has the additional benefit of establishing a fairly narrow price range for a riparian buffer strip, between $210 and $370 per hectare ($85 and $150 per acre) for about 97.9% of the potential agricultural buffer area. Though well-functioning markets generally establish their own equilibrium prices and quantities, the methods and the predictive information in this research may be valuable to conservation program managers or those seeking to establish market-based tradable discharge permit systems. For example, these estimates (or estimates specific to another watershed created using these methods and procedures), along with an analysis of the environmental benefits associated with the potential buffer strips, might be used to provide a starting point for a program manager initiating a reverse auction for buffer strips. The next step in predicting market behavior is to use in-depth water quality modeling to convert this buffer supply curve into an NPS nutrient reduction credit supply curve. Further research could quantify the marginal willingness of point sources to pay, or the demand for NPS nutrient reduction credits in the watershed.

There are obvious limitations to this study, many of which result from data limitations. For example, the riparian shape files from the National Hydrography Dataset are line features (i.e., they have no area), as opposed to the land use polygon features, meaning that the actual shared boundaries between agricultural lands and waterways are sometimes not found within a 45.7 meter (150-feet) buffer around the riparian line features. This means that available buffer area may be underrepresented in some areas, especially on the main stem of the Harpeth River, where wide waters are represented by a line. Yet, agricultural activities are not nearly as abundant near the main stem as they are in the upper reaches, or eastern portion, of the Harpeth River watershed. Thus, this data limitation may not be as pronounced as one might expect if agricultural activities were distributed more evenly throughout the watershed. The issue of error in stream-land-use-interface identification also contributes to error in the calculation of exclusion fencing costs for pasture land, which depend on the shape and size of the potential buffer features as determined, in part, by proximity to the riparian line features. These data limitations were also a factor in the choice of a 45.7-meter (150-feet) buffer strip width, which is greater than that typically found in existing regulations and recommendations. In this sense, the cost estimates can be thought of as an upward bound on the true costs of a buffer strip requirement for the Harpeth River watershed. Ideally, data that show the shapes and areas of all riparian features in the watershed should be used; however, such data are not currently available for a sufficiently large region.

These methods and procedures do not account for the cost of alternate watering systems for cattle that are to be excluded from stream access. These costs should be included, because they would be incurred as a direct result of complete cattle exclusion; however, to calculate such costs, the cattle stocking rates of potential pasture buffers would be required, as well as the elements of the "pasture/hay" land-use classification that are pasture, as opposed to hay. In addition, given that the supply curve for leased pasture is unlikely to be horizontal due to differences in suitability, location, and operations, there is likely to be an unknown number of landowners unwilling to lease their land at the market equilibrium rate. Thus, using an average rental rate as a proxy for the opportunity cost of pasture

land underestimates the true opportunity cost for those producers who would be unwilling to lease their land at that rate.

Additionally, farmers who establish BMPs such as buffer strips are also likely to modify practices elsewhere in their operations. For example, Norwood and Chvosta found that some swine producers facing phosphorus-based caps on swine effluent land application rates would respond by clearing timberland to increase the area available for swine effluent disposal, while others would reduce swine production. Thus, such potential modifications may have adverse results or provide unexpected benefits for society as a whole. This study does not account for the possibility of private benefits from harvesting grasses or trees from the buffer strip. Nor does it account for the benefits landowners may derive from reduced erosion and increased stream bank stability provided by buffer strips. These latter benefits, inasmuch as agricultural producers believe they exist, will reduce their perceived opportunity costs, thus reducing the total cost of any given level of buffer strip implementation below that indicated by the supply schedule. To assess these potential private benefits, extensive in situ work and modeling would need to be performed so that the reduced effects of erosion could be estimated and monetized for each potential buffer strip. Such modeling could also be used to estimate each possible buffer strip's potential to reduce sediment and nutrient loadings and to develop a supply curve for emission reduction credits from NPSs.

The supply of agricultural riparian buffer strips will change substantially with the passage of time, especially in a rapidly developing area like the Harpeth River watershed, which is home to Nashville and its rapidly expanding suburban development. Thus, the potential for agricultural NPS reductions changes as land use changes. In this particular watershed, as in most, NPS remains the major source of nutrient loadings; however, an increasing proportion of these loadings come from urban and suburban land, as agricultural land is being converted to nonagricultural uses. These situations are not static, and equilibrium for a market in buffer strips will be constantly changing, especially in watersheds that are rapidly developing. For example, it is important to note that the estimates of annualized buffer strip costs and supply provided in this article do not account for the possibility of increased returns due to the conversion of land from agriculture to a higher valued use. While the narrow scope of the regulation being considered (requiring only that buffer strips be installed on agricultural lands) obviates the need for estimating the costs associated with buffer strips for other land uses, the possibility of agricultural land bordering a stream being converted to another use still presents problems. If the land use change resulted in the loss of the buffer strip, then establishment costs could no longer be annualized over the estimated "life" of the buffer strip, in which case actual annualized costs would exceed estimates of those costs. Alternatively, the relative importance of these establishment costs likely means that a voluntary program would require long-term commitments on the part of farmers to maintain buffer strips in order to recoup these costs. The longer and more restrictive the commitment, the more likely that farmers would be required to sacrifice, at least temporarily, greater returns from a change in land use, and the less likely that farmers would be willing to enroll in the program for the amounts estimated in this analysis. As a result, estimates of buffer strip costs or farmer participation in a voluntary program in areas with significant potential

for land-use change should likely be interpreted as either a lower bound in the case of costs or an upper bound in terms of farmer participation.

Thus, there is still much work to be done. However, this article illustrates how spatial variation in the opportunity costs of land used for buffer strips could be captured with commonly available data on soils, crop yields, and crop production budgets. As such, the article contributes to the important task of evaluating the costs of policies imposing buffer strip requirements on agricultural activities and the possible supply of buffer strips in response to policies that promote buffer strip adoption through direct subsidies or the purchase of pollution reduction credits in a WQT program.

Endnotes

[1]On the other hand, the CWA explicitly includes "concentrated animal feeding operations" (CAFOs) within the definition of point sources and, as a result, CAFOs are required to obtain CWA permits and adhere to the terms of those permits.

[2]Vogelmann et al., describe the process by which satellite imagery was manipulated and interpreted to produce these data. For many areas of the country, more recent versions of the NLCD are now available (http://www.mrlc.gov/).

[3]It should be noted that this assumption drastically simplifies what occurs on the ground, as each crop is suited to different growing conditions. In reality, crop composition varies throughout a county, but we only have access to county-level data on crop composition.

[4]This assumption is trivial in that expected yields were not close to zero for any potential riparian buffer strip. Furthermore, if a producer expects very low crop yields at a location, the land is likely to be put to other use, and would not be classified as cropland in the 1992 NLCD. The assumption is useful, however, because it allows us to estimate net returns for expected yields lower than the yield goals included in the available budgets. Also, as expected yield potential decreases, it seems likely that producers will reduce inputs proportionately (where possible), thus making linear interpolation a reasonable method for estimating net returns.

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