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CROPLAND RIPARIAN BUFFERS THROUGHOUT CHESAPEAKE BAY WATERSHED: SPATIAL PATTERNS AND EFFECTS ON NITRATE LOADS DELIVERED TO STREAMS[1]

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ABSTRACT: We used statistical models to provide the first empirical estimates of riparian buffer effects on the cropland nitrate load to streams throughout the Chesapeake Bay watershed. For each of 1,964 subbasins, we quantified the 1990 prevalence of cropland and riparian buffers. Cropland was considered buffered if the topographic flow path connecting it to a stream traversed a streamside forest or wetland. We applied a model that predicts stream nitrate concentration based on physiographic province and the watershed proportions of unbuffered and buffered cropland. We used another model to predict annual streamflow based on precipitation and temperature, and then multiplied the predicted flows and concentrations to estimate 1990 annual nitrate loads. Across the entire Chesapeake watershed, croplands released 92.3 Gg of nitrate nitrogen, but 19.8 Gg of that was removed by riparian buffers. At most, 29.4 Gg more might have been removed if buffer gaps were restored so that all cropland was buffered. The other 43.1 Gg of cropland load cannot be addressed with riparian buffers. The Coastal Plain physiographic province provided 52% of the existing buffer reduction of Bay-wide nitrate loads and 36% of potential additional removal from buffer restoration in cropland buffer gaps. Existing and restorable nitrate removal in buffers were lower in the other three major provinces because of less cropland, lower buffer prevalence, and lower average buffer nitrate removal efficiency.

(KEY TERMS: watersheds; geospatial analysis; nonpoint source pollution; watershed management; nitrate nitrogen; riparian buffer; cropland; flow-path analysis; Chesapeake Bay.)

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INTRODUCTION

Nonpoint source pollution of aquatic systems is a worldwide problem (Carpenter *et al.*, 1998). For coastal waters, including the Chesapeake Bay, nitrogen (N) pollution is especially harmful (Boesch *et al.*, 2001; Rabalais *et al.*, 2001; Boesch, 2002), and the Environmental Protection Agency has begun to enforce reductions in the delivery of nitrogen and other pollutants to the Chesapeake Bay from its watershed (USEPA, 2010b, c). Nonpoint source pollution from cropland is the dominant source of nitrogen in the Chesapeake Bay watershed (Jordan *et al.*, 1997a, b; Ator *et al.*, 2011). Fertilizer application, tilling, and nitrogen fixation on croplands all promote nutrient loss, and much of the nutrients resulting from animal agriculture are also associated with

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croplands because animal manure is typically applied to cropland (Jordan and Weller, 1996). Streamside forests (riparian buffers) can remove nutrients lost from uphill disturbed areas, so conservation and restoration of riparian buffers are frequently recommended to help control nonpoint source pollution (Lowrance *et al.*, 1997; Dosskey *et al.*, 2010). More than half of the watershed restoration projects undertaken in the Chesapeake Bay drainage before 2003 involved riparian reforestation (Hassett *et al.*, 2005).

Strong evidence for nutrient removal by riparian buffers has come from intensive field sampling of small study areas (Lowrance *et al.*, 1997; Mayer *et al.*, 2007). Efforts to demonstrate buffer effects for whole watersheds with empirical statistical models have been more equivocal, partly because the geographic methods used to quantify buffer prevalence and the statistical models used to relate land cover patterns to stream discharges have been inadequate (Weller *et al.*, 2011). Simulation models have been applied to extrapolate *assumed* buffer effects across watersheds (e.g., USEPA, 2010a), but we know of no studies that have empirically quantified the watershed-wide effects of riparian buffers on nutrient loads in the Chesapeake watershed or any other large drainage basin.

In previous publications, we reviewed problems that have limited efforts to model buffer effects in watersheds (Weller *et al.*, 2011). To overcome those problems, we developed functionally based geographic methods to quantify buffer prevalence and parsimonious statistical models to document buffer effects and calculate nutrient removal in buffers. We applied the new methods to a sample of small watersheds in three of the four major physiographic provinces of the Chesapeake drainage. We estimated the circa 1990 effects of riparian buffers on stream nitrogen concentrations in the study watersheds and the maximum additional removal that might be achieved by restoring riparian buffers in cropland buffer gaps so that all croplands were buffered. The main findings of those efforts (Weller *et al.*, 2011) include:

1. Buffers cannot act as sinks unless they are positioned along flow pathways to intercept materials lost from source areas.
2. Understanding watershed-wide buffer effects requires four steps: identifying flow paths from sources to streams, quantifying buffer prevalence along those paths, estimating nutrient removal in buffers, and aggregating across all the flow paths in a watershed.
3. Statistical models of buffer effects on watershed nutrient discharges have been limited by spatial and statistical methods used.
4. Fixed-width buffer metrics do not describe buffer positioning relative to sources.
5. Flow-path analysis describes buffer prevalence along the pathways that connect source areas to streams and "scales-up" from transects to whole watersheds.
6. Stepwise multiple regression provides a surfeit of candidate models and cannot calculate removal by buffers.
7. Carefully constructed parsimonious models provide discerning tests for buffer effects, estimates of removal by existing buffers, and estimates of possible additional removal from restoring buffers in existing buffer gaps.
8. Models that do not account for buffers can predict stream nutrient levels, but yield misleading information about material sources and fates.
9. Omitting buffers from management models may lead to ineffective management action and targeting.

In this study, we enhance and extend our previous analyses to provide the first Chesapeake-wide estimates of how much riparian buffers reduce the load of cropland nitrate to streams. We apply flow-path analysis to quantify cropland and buffer prevalence throughout the entire 166,700-km^2 watershed, extend the calibration of the nitrate concentration model from three to all four major physiographic provinces of the Chesapeake drainage, implement a very accurate model of average annual stream discharge to convert nitrate concentration predictions to nitrate yields and loads, and use bootstrapping to estimate uncertainties for all model coefficients, model predictions, and summaries of those predictions. We report the amounts of and spatial patterns in cropland and buffer prevalence, nitrate loss from cropland, nitrate removal in buffers, nitrate delivery to streams, and potential additional removal from buffer restoration in cropland buffer gaps.

METHODS

Study Area

We analyzed the Chesapeake Bay drainage basin as delimited by the national watershed boundary dataset (USGS and USDA-NRCS, 2012). This spatial dataset divides the Chesapeake Bay watershed into 1,979 subwatersheds (called 12-digit hydrologic units). Fifteen of the units contained no land, and other coastal units included some offshore open water. Eliminating the all-water units and areas of offshore open water left 1,964 units (Figure 1) averaging 87 km^2 in area and summing to 166,700 km^2, the total area of the Chesapeake Bay drainage.

We subdivided the drainage basin into its four major physiographic provinces using a digital map of hydrogeomorphic regions (Brakebill and Kelley, 2000) and aggregating its 11 categories into four major provinces: Coastal Plain (CP) (combining USGS categories CPD, CPL, and CPU); Piedmont (PD) (combining USGS categories ML, PCA, and PCR); Appalachian Mountain (AM) (combining USGS categories BR, VRC, and VRS); and Appalachian Plateau (AP) (combining USGS categories APC and APS), and omitting open water (USGS category h2o). We use two letter abbreviations for the four major provinces: Coastal Plain, Piedmont, Appalachian Mountain, and Appalachian Plateau (CP, PD, AM, and AP).

Some of the hydrologic units lay astride physiographic province boundaries or the boundaries between states. To facilitate later summaries of provinces or state results, we further subdivided those units by the physiographic province boundaries (Langland *et al.*, 1995) and state boundaries (ESRI, 2003) to obtain 2,269 analysis watersheds each completely within one physiographic province and one state (Figure 1).

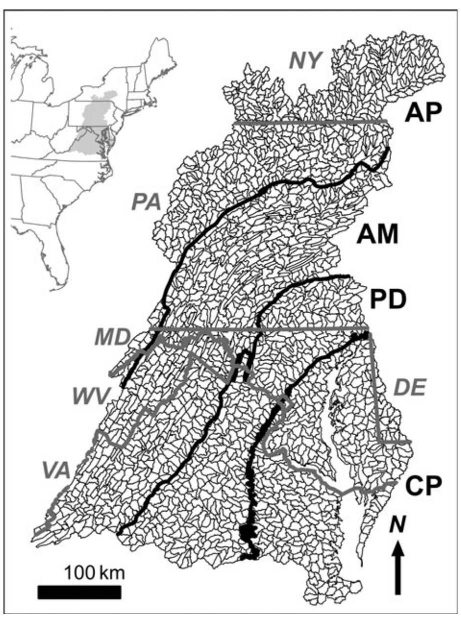

FIGURE 1. The Chesapeake Bay Watershed. Subwatersheds (12-digit hydrologic units, USGS and USDA-NRCS, 2012) were further divided into analysis units using boundaries of states (gray lines and gray italic letters) and major physiographic provinces (black lines and black bold letters). The provinces are the Coastal Plain (CP), Piedmont (PD), Appalachian Mountain (AM), and Appalachian Plateau (AP). The inset shows the location of the Chesapeake basin within the eastern United States.

Geographic Analysis of Cropland and Riparian Buffers

We quantified the amount of cropland in each analysis watershed using the cropland category (land cover code 82) of the circa 1990 National Land Cover Dataset (called "NLCD 1992," Vogelmann *et al.*, 1998a, b; USEPA 2007), which has 30-m^2 pixels. The circa 1990 version is the NLCD dataset closest in time to the watershed study (Liu *et al.*, 2000) that provided stream nitrate concentration data for calibrating the nitrate model (below). We calculated cropland proportion (C) relative to the total land area in the analysis watershed (total area minus the area of water, NLCD land cover code 11). After subtracting NLCD water pixels (2,739 km^2), the total land area of the Chesapeake Bay drainage is 163,930 km^2.

Flow-Path Analysis. We characterized the prevalence of riparian buffers in each analysis watershed using a measure of buffer presence along the flow paths linking croplands to streams (Baker *et al.*, 2006b). Briefly, for every cropland pixel, we used the digital elevation model (30 m National Elevation Dataset, Gesch *et al.*, 2002) to identify the steepest descent surface transport pathway (O'Callaghan and Mark, 1984) connecting that cropland pixel to a stream mapped in the 1:24,000 National Hydrography Dataset (Simley and Carswell, 2009). We then determined whether or not each path went through a riparian buffer, where riparian buffer was defined as forest or wetland land cover (land cover codes 41-43, 51, 91, or 92 in NCLD 1992 dataset) that overlay or was contiguous with a mapped stream (i.e., connected to the stream channel by an unbroken chain of forest or wetland pixels, Baker *et al.*, 2006b). The presence or absence of riparian buffer was summarized across all the cropland pixels to estimate buffer prevalence in the analysis watershed as the frequency of buffer gaps below cropland (Weller *et al.*, 1998). We used this measure ($FGAP_c$) to divide the cropland in each analysis watershed into unbuffered cropland ($C_u = C FGAP_c$) and buffered cropland ($C_b = C - C_u$). Like C, C_u and C_b are the proportions of their respective land areas relative to total watershed land area (excluding water). Full details of the flow-path analysis are given in Baker *et al.* (2006b) and Weller *et al.* (2011).

We emphasize that the flow-path analysis method is not a surface water model, even though it infers flow direction based on surface topography. The algorithm models the likely transport paths of both surface and shallow subsurface waters. By using surface topography, we make the simplifying assumption that water generally flows downhill. Fine-scale groundwater flow directions can certainly differ from surface topography at specific locations. However, incorporating those subsurface details in broad regional models is conceptually and computationally challenging, high-resolution topographic and hydrological data are not universally available, nor is it clear that such data would necessarily improve model performance. Until those challenges are overcome, inferring generalized flow directions by applying the flow-path algorithm to widely available topographic data yields new and useful information on buffer prevalence and effects on cropland nitrate delivery to streams across large areas (Weller *et al.*, 2011).

Stream Nitrate Concentration

Model Calibration. We adapted our published statistical model (Weller *et al.*, 2011) to predict the nitrate concentration in the stream draining each analysis watershed. Briefly, the linear statistical model predicts stream nitrate concentration based on the proportions of cropland (C) and unbuffered cropland (C_u) in a watershed, and differences among physiographic provinces are accommodated by fitting province-specific parameters. Previously, we calibrated the model using average base-flow nitrate concentrations leaving 321 watersheds in the CP, PD, and AM provinces (Weller *et al.*, 2011). For this analysis, we also included nitrate data from 64 watersheds in the AP province for a total of 385 calibration watersheds. Previous studies provide more information on watershed selection, water sampling, and nitrate concentration measurement (Liu *et al.*, 2000) and on the geographic characteristics (especially cropland and buffer prevalence) of the calibration watersheds (Baker *et al.*, 2006a, b, 2007; Weller *et al.*, 2011). As before, we used information theoretic methods (Akaike's Information Criterion AICc, Burnham and Anderson, 2002) to compare among five alternate nitrate models and arrive at a final model.

Nitrate Source and Buffer Nitrate Removal Potentials. As before (Weller *et al.*, 2011, p. 1683), the coefficients of the fitted nitrate concentration model provided estimates for each physiographic province of nitrate source and buffer nitrate removal potentials, including edge-of-field loss of nitrate from cropland, buffer nitrate removal, nitrate loss from buffered cropland, and nitrate loss from other land types. The ratio of removal by buffers to edge-of-field loss gives the relative nitrate removal potential for a province expressed as a fraction or percentage of input to buffers from cropland (see Eq. 12 in Weller *et al.*, 2011). This number is often called percent removal or buffer efficiency.

Nitrate Sources and Buffer Nitrate Removal in the Analysis Watersheds. As before (Weller *et al.*, 2011, p. 1684), we applied the fitted nitrate model to each analysis watershed using the actual land cover data to predict the stream nitrate concentration and to divide the stream nitrate into components (Table 1): N_3, cropland nitrate that could be removed from the stream by restoring buffers in all buffer gaps downhill from cropland so that all cropland is buffered "possible removal in restored buffer gaps"; N_2, cropland nitrate that would still reach the stream even if all cropland were buffered "buffer transmission"; and N_{01}, the expected nitrate concentration if all cropping were abandoned or all cropland were converted to other land uses. We also estimated N_4, the additional nitrate that would reach the stream if existing buffers were removed so that no cropland was buffered "removal by existing buffers." Unlike our previous analysis, we used the proportion of cropland (C) to divide the background component (N_{01}) into two parts: the nitrate from cropland if cropping were abandoned ($N_1 = CN_{01}$) "background from cropland" and nitrate from other land covers $N_0 = (1 - C)\,N_{01}$. The components can be summed to estimate other quantities listed in Table 1 (see Weller *et al.*, 2011 for equations and more detailed explanation).

We emphasize that the statistical nitrate model does not assume or infer any particular biogeochemical mechanism of nitrate removal in riparian buffers.

TABLE 1. Components of Stream Nitrate Levels.

Nitrate Component	Symbol
Sources of nitrate to stream water	
Other land covers	N_0
Background from cropland	N_1
Buffer transmission	N_2
Possible removal in restored buffer gaps	N_3
Removal by existing buffers	N_4
Sums of cropland nitrate components	
Originating in cropland	$N_1 + N_2 + N_3 + N_4$
Due to cropping activity	$N_2 + N_3 + N_4$
Not controllable by buffers	$N_1 + N_2$
Controllable by buffers	$N_3 + N_4$
Cropland contribution to stream nitrate under different scenarios	
With no crops	N_1
With all buffer gaps restored	$N_1 + N_2$
With existing buffers	$N_1 + N_2 + N_3$
With no buffers	$N_1 + N_2 + N_3 + N_4$
Total stream nitrate under different scenarios	
With no crops	$N_0 + N_1$
With all buffer gaps restored	$N_0 + N_1 + N_2$
With existing buffers	$N_0 + N_1 + N_2 + N_3$
With no buffers	$N_0 + N_1 + N_2 + N_3 + N_4$

Notes: The glossary (Table S6) provides additional terms and details.

Nor does the model assume or infer a specific hydrological or biogeochemical explanation for why some of the nitrate evades removal in buffers. The model *does* show that, among watersheds, higher prevalence of streamside buffers along the transport pathways connecting cropland with streams is associated with lower stream nitrate concentrations. The models can also estimate the amount of nitrate removal in buffers and the amount of nitrate transmission through buffers (regardless of the mechanisms) that must be invoked to account for the observed association.

In this study, we focus on interpreting the amount and fate of nitrate originating in cropland (N_1–N_4 and their sums, Table 1). The model does estimate the nonpoint nitrate contributions from all other land covers (N_0); however, model results are more reliable for cropland because the study watersheds used to calibrate the model were mainly rural watersheds and did not adequately sample other nitrate source areas, such as developed lands (Weller *et al.*, 2011).

Stream Discharge

To estimate the stream discharge leaving each analysis watershed, we applied a statistical model that predicts average annual stream discharge (Q) from watershed area and average annual precipitation and temperature (Vogel *et al.*, 1999). The published model for the mid-Atlantic region was calibrated for 166 watersheds and achieved an adjusted R^2 value of 99.4% (region 2 in Vogel *et al.*, 1999). Ian Wilson and Richard Vogel (personal communication) provided the flow, precipitation, temperature, and area data underlying the published model for use in bootstrapping analysis. To provide temperature and precipitation data for our analysis watersheds, we spatially summarized the 1971-2000 "800-m annual climatology normals" from the PRISM climate data (Daly *et al.*, 2002; PRISM 2007) for the analysis units. The discharge model is a linear equation that predicts log-transformed streamflow based on log-transformed independent variables. To avoid the bias that arises when antilog transforming log predictions, we multiplied each back-transformed prediction by the correction factor $e^{s^2/2}$, where s is the standard error of the fitted linear (log-log) regression (Sprugel, 1983).

Nitrate Yield and Load

For each analysis watershed, we multiplied the predicted stream nitrate concentration by the predicted water discharge to obtain predicted annual nitrate yield (kg nitrate-N/ha) and annual nitrate load (Mg nitrate-N). We did the same for the concentration components (e.g., N_0-N_4 and sums described above, Table 1) to convert them to yields and loads.

Uncertainty Analysis

We estimated confidence limits for model parameters and for all model predictions with bootstrapping (Efron and Gong, 1983). For the nitrate and stream discharge models, we sampled the calibration datasets with replacement to obtain 10,001 bootstrap samples having the same number of observations as the original datasets. For the nitrate model, we resampled each province separately so that bootstrap samples preserved the original province sample sizes. The nitrate model and streamflow model were both refit for each bootstrap sample, and then applied to estimate the concentration, discharge, yield, and load predictions described above for all of the analysis watersheds. Predictions were summed or averaged across all the analysis units in a physiographic province, state, or the entire Chesapeake basin. This gave a distribution of 10,001 predicted values for every summary statistic. We used the 2.5th and 97.5th percentiles of the distribution as the 95% confidence limits of a summary statistic. We also used bootstrapping to estimate the confidence limits of the nitrate model parameters and of relative nitrate removal potential (removal by buffers/buffer input) calculated using the parameters of the 10,001 fitted nitrate models (as described by Eq. 12 in Weller *et al.*, 2011).

For every estimate and its confidence interval, we also calculated % relative error, defined as 100 times half the width of the confidence interval divided by the estimate. For example, we could say that an estimate with a 12% relative error is known within ±12%.

Analysis and Reporting

We used the ArcGIS Geographic Information System (ESRI, Inc., Redlands, California) for all spatial analyses and for drawing maps. We used the R and SAS packages for statistical analyses (SAS Institute Inc., 2004; R Core Team, 2012). We summarized independent variables and predictions (with 95% confidence limits) by physiographic province, by state, and for the entire Chesapeake drainage; and we displayed the summary results with histograms and tables. We also summarized among the analysis watersheds in each hydrologic unit to yield the independent variables and model predictions for every hydrologic unit. This summarization recombined pieces of hydrologic units that had been separated by state or physiographic province boundaries. We created maps of independent variables (e.g., cropland, buffer gaps, or precipitation) and model predictions (e.g., streamflow, nitrate concentration, or buffer nitrate removal) shaded by hydrologic unit to illustrate spatial variation among hydrologic units across the Chesapeake drainage. Quintile shadings were generated by dividing the values of each variable into five evenly distributed level groups.

RESULTS

Geographic Analysis of Cropland and Riparian Buffers

According to the NLCD land cover data, cropland occupies a small proportion (6.7%) of Chesapeake Bay watershed, and cropland prevalence differs among the four physiographic provinces (Figure 2). The proportion of cropland in the CP (17.5% of land area) is more than three times higher than in the other provinces (PD, AM, and AP are 5.6, 4.5, and 3.0% cropland, respectively). Buffer prevalence downhill from cropland also varies among provinces. Almost half the CP cropland is buffered (49.6%), and buffer prevalence is nearly as high in AP (47.3% of cropland), although the total proportion of cropland is quite low in the AP (3% of land area). Buffer prevalence is lower in PD (34.5% of cropland buffered) and lowest in AM (25.2% buffered). Overall, about two-fifths (40.7%) of the cropland in the Chesapeake watershed is buffered by streamside forest or wetland wide enough to be detectable in the NLCD land cover data.

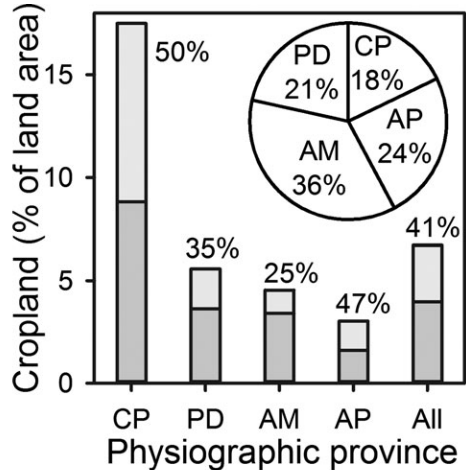

FIGURE 2. Cropland Proportions in the Major Physiographic Provinces of the Chesapeake Bay Watershed (CP, Coastal Plain; PD, Piedmont; AM, Appalachian Mountain; and AP, Appalachian Plateau) and in the Entire Basin (All). Bars are divided into unbuffered (dark gray) and buffered (light gray) cropland. The numbers above the bars give the percent of cropland in each region that is buffered. The inset shows the percentage of the Chesapeake Bay watershed area (163,930 km^2 excluding water) within each province. Table S1 gives numerical values.

Cropland and buffer prevalence also vary within provinces (Figure 3). Within the CP, cropland occupies a higher proportion of the land on the eastern shore of the Bay than on western shore. PD cropland

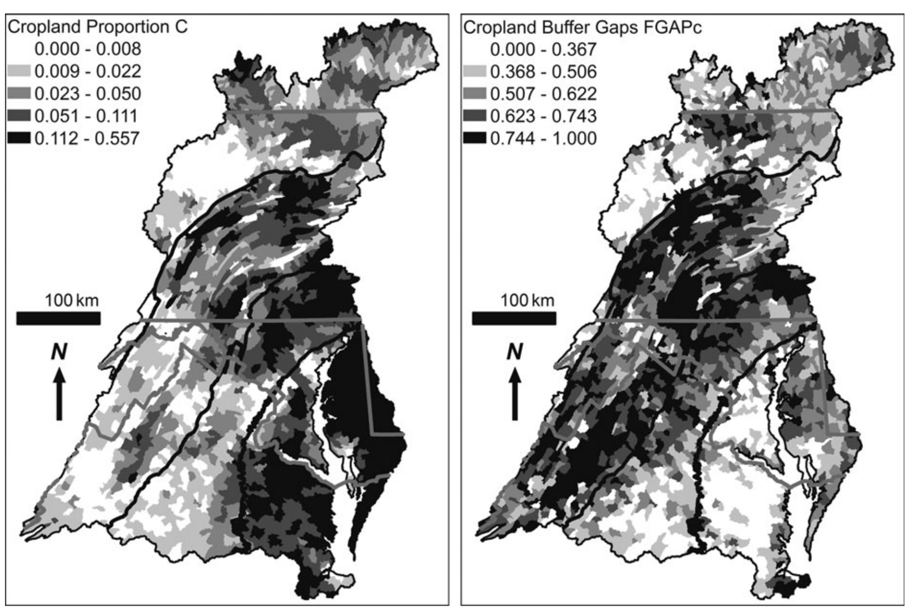

FIGURE 3. Fractions of Cropland (C) and Buffer Gaps below Cropland ($FGAP_c$) in the Hydrologic Units.

is concentrated in the northeastern part of PD in agricultural areas of southern Pennsylvania. Appalachian cropland is concentrated in flat valley areas between ridges.

The spatial patterns in buffer prevalence differ from the patterns of cropland proportion (Figure 3). Buffer gap fraction is high throughout the AM province. Buffer gap fraction is lowest in CP on the western shore of Chesapeake Bay and in southern PD. The CP on the eastern shore of the Bay has more cropland buffer gaps than on the western shore, but less than the AM province. The pattern of unbuffered cropland follows the regional pattern of total cropland because unbuffered cropland is calculated from total cropland ($C_u = C$ $FGAP_c$).

Stream Nitrate Concentration

Model Calibration. We fit linear statistical models to predict stream nitrate concentration based on physiographic province and the amounts of total and unbuffered cropland in a watershed expressed as proportions of watershed area. Previously, we applied model averaging (Burnham and Anderson, 2002) to five alternate linear models to derive a "model average" for predicting nitrate concentrations (Weller *et al.*, 2011). After we added 64 AP study watersheds in the present analysis, we fit the same five models, and one model (the BFp model described in the Appendix here and by Eq. 7 and Table 2 in Weller *et al.*, 2011) among the five emerged as the best model. It explained three-fourths of the variability (R^2 = 75.6%) in measured nitrate concentration among the 385 calibration watersheds and it had a model probability (Burnham and Anderson, 2002) of 0.94, about 16 times higher than the probability (0.06) of the next best model (Table S2). Selecting the BFp model as a single best model instead of applying model averaging simplified the presentation of results and the bootstrapping analysis of model uncertainty (below).

Nitrate Source and Nitrate Removal Potentials. The fitted coefficients of the stream nitrate concentration model represent the province-average nitrate-source strengths of cropland and noncropland and the nitrate removal potential of buffer below croplands (Table 2). All the coefficients have units of concentration (mg nitrate-N/l). The quantity of nitrate leaving croplands (also the amount entering streams from unbuffered cropland) is highest in the PD province (32.3), intermediate and nearly equal in AM (21.7) and AP provinces (22.1), and significantly lower in the CP (10.7). The loss to streams from buffered cropland is lower than from unbuffered cropland in all provinces, but still highest in the PD province (22.1), intermediate and nearly equal in Appalachian provinces (Mountain 11.5 and Plateau 11.9), and lowest in CP (0.51).

The percent of nitrate removal (often called buffer efficiency) differs among provinces even though the absolute difference between buffered and unbuffered cropland losses is 10.2 for all provinces (coefficient β_u, Table 2). Percent removal (100*[1 – buffer output/buffer input], Table 3) is very high in the CP (95%), intermediate in the AM provinces (~46%), and lowest in the PD (32%).

TABLE 2. Coefficients for the Model Predicting Stream Nitrate Concentrations Based on Cropland, Unbuffered Cropland, and Physiographic Province.

Model Component	Symbol	Coefficient	SE	95% CI	Relative% Error
Intercept (nitrate from all land covers)					
All	β_0	0.35	0.09	[0.20, 0.51]	45
Cropland (nitrate from all cropland)					
CP	β_c	0.51	1.29	[−2.93, 3.81]	662
PD	$\beta_c + \beta_{cp}$	22.13	1.75	[15.56, 27.34]	27
AM	$\beta_c + \beta_{ca}$	11.49	2.11	[5.09, 17.57]	54
AP	$\beta_c + \beta_{ch}$	11.87	3.79	[4.16, 18.81]	62
Unbuffered cropland (additional nitrate from unbuffered cropland)					
All	β_u	10.21	1.83	[4.59, 16.26]	57
Total from unbuffered cropland					
CP	$\beta_c + \beta_u$	10.72	0.94	[7.68, 13.79]	29
PD	$\beta_c + \beta_{cp} + \beta_u$	32.34	1.03	[27.83, 35.75]	12
AM	$\beta_c + \beta_{ca} + \beta_u$	21.70	1.15	[18.70, 24.71]	14
AP	$\beta_c + \beta_{ch} + \beta_u$	22.08	3.69	[14.90, 28.88]	32

Notes: All coefficients have units of mg nitrate N/l. All coefficients except β_c are statistically significant ($p < 0.002$), but β_c is not significant ($p = 0.7$). The 95% confidence intervals (CI) were estimated by bootstrapping, not from the standard error (SE). Relative% error is 100 times half the 95% CI divided by the coefficient. The Appendix provides the model equation and defines the coefficient symbols. The provinces are the Coastal Plain (CP), Piedmont (PD), Appalachian Mountain (AM), and Appalachian Plateau (AP).

TABLE 3. Relative Nitrate Removal Potentials (buffer efficiency) with 95% Confidence Intervals.

Province	% Removal	95% CI
Coastal Plain	95	[57, 123]
Piedmont	32	[15, 50]
Appalachian Mountain	47	[22, 76]
Appalachian Plateau	46	[23, 76]

Notes: Calculated as in Eq. (12) in Weller *et al.* (2011). Confidence intervals from bootstrapping.

The model coefficients and nitrate removal potentials for three provinces are numerically quite similar to those previously reported for a smaller calibration dataset without the AP study watersheds, and that previous report includes a more detailed derivation and explanation of how the model coefficients are interpreted (Weller *et al.*, 2011). The coefficients for the AP are numerically similar to and not statistically different from the coefficients for the AM province, suggesting that the two provinces might be combined in future analyses.

Stream Discharge

Average annual stream yields (Q_{cm}) predicted by the regional regression model (Vogel *et al.*, 1999) ranged from 32.3 to 83.9 cm among the hydrologic units (Figure 4). Higher stream yields were associated with

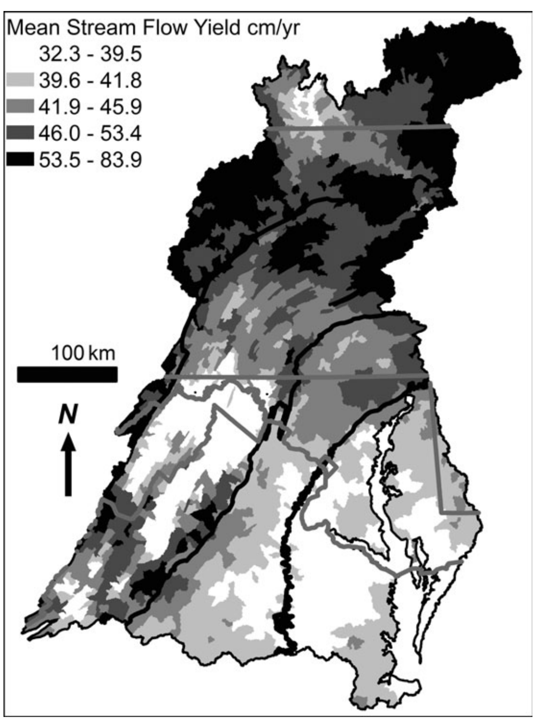

FIGURE 4. Predicted Average Annual Stream Yield (cm) for the Hydrologic Units. 1 cm = 100,000 l/ha = 100 m^3/ha.

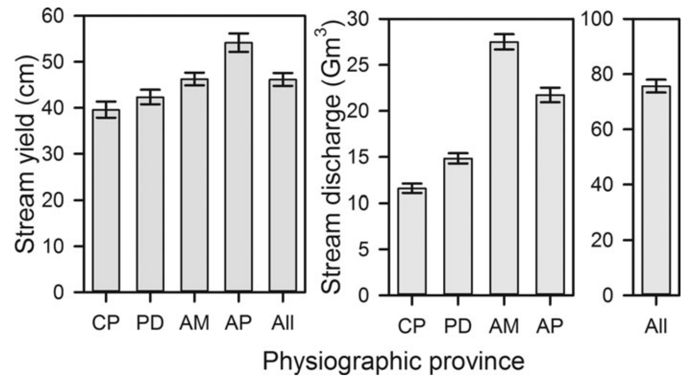

FIGURE 5. Predicted Average Annual Stream Yield (cm) and Stream Discharge (Gm^3) for the Major Physiographic Provinces and for the Entire Chesapeake Watershed. 95% Confidence intervals are from bootstrapping. Those confidence intervals represent ±3-4% relative percentage error for all quantities in the figure. 1 cm = 100,000 l/ha = 100 m^3/ha. The provinces are the Coastal Plain (CP), Piedmont (PD), Appalachian Mountain (AM), and Appalachian Plateau (AP).

cooler areas and with higher precipitation in the mountains or near the Chesapeake Bay (Figure S2). Province average stream yields were lowest for the CP and went up in the order PD < AM < AP (Figure 5). When the unit area yields were multiplied by province areas to obtain total annual stream discharge volumes (Q) for the provinces, the AM province had the highest discharge (Figure 5), primarily because it is larger than any of the other provinces (the AM province is 36% of the Chesapeake watershed while the other provinces are each near 20% of the Chesapeake watershed) (Figure 2).

Nitrate Yield and Load

Applying the nitrogen model to the geographic data from the analysis units (Figure 2) estimates the stream concentration for each unit and quantifies the components that represent nitrate sources and removal by buffers in each unit (Table 1). Multiplying the predicted concentrations and components by the predicted average annual water yield and then by watershed area produces estimates of stream nitrate levels and nitrate components as average annual yields (kg N/ha) and loads (Mg N).

Summing the average annual loads for the entire Chesapeake watershed provides the most integrated view of the results (Figure 6, right). Circa 1990, croplands released 92.3 Gg of nitrate nitrogen, but 19.8 Gg of that was removed by riparian buffers so that the cropland nitrate load to streams was 72.5 Gg. At most, 29.4 Gg more might have been removed through a buffer restoration that addressed all cropland runoff. The remainder of cropland load (43.1 Gg)

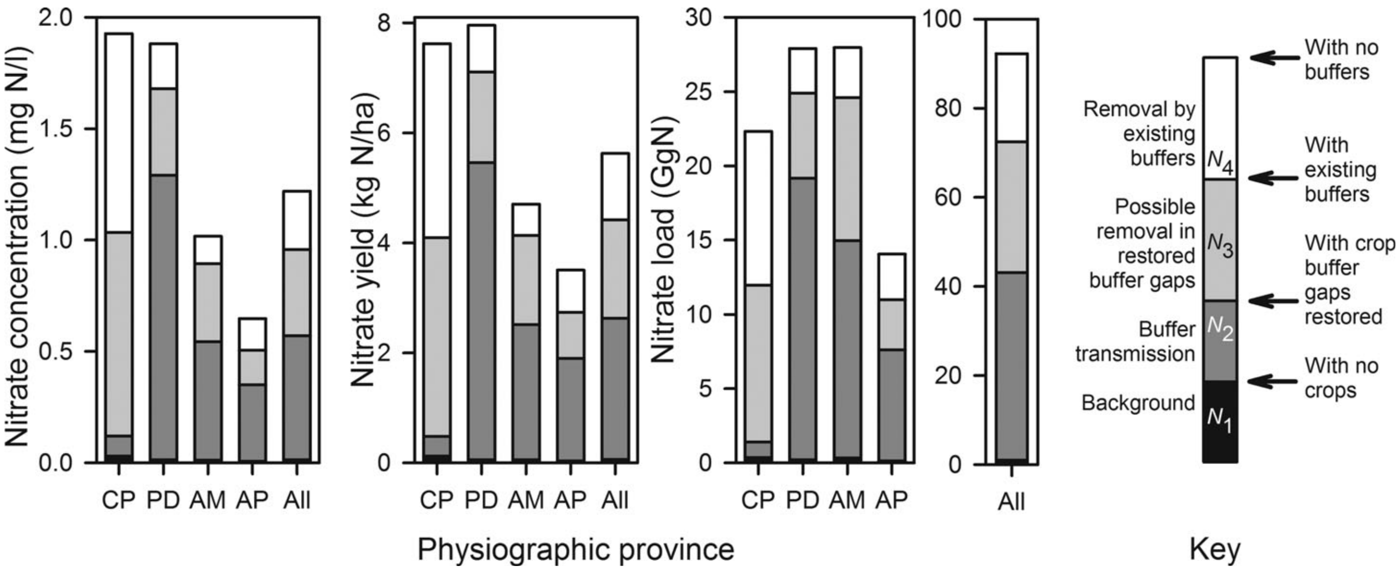

FIGURE 6. Components of Stream Levels of Nitrate Originating in Cropland. Results are summarized for four major physiographic provinces and for the entire Chesapeake watershed. Left, average nitrate concentration (mg N/l); middle: average nitrate yield (kg N/ha); right: nitrate load (Gg N). The key at right associates shadings with components (N_1-N_4) and illustrates how components sum to give stream levels of cropland nitrate under different scenarios (see Table 1). The Appendix shows how components are calculated from the statistical model equation. The provinces are the Coastal Plain (CP), Piedmont (PD), Appalachian Mountain (AM), and Appalachian Plateau (AP).

must be addressed by other management practices. The remainder is mostly nitrate that would pass through buffers and reach streams even if all cropland were buffered, but 1.0 Gg of the remainder is the background load that would be released if cropping activities on the cropland were stopped. The model also predicts that other land uses would deliver an additional 25.1 Gg of nitrate, for a total load to streams of 97.6 Gg. This contribution from other land uses is certainly an underestimate because the watersheds used to calibrate the model were selected to emphasize cropland (Liu *et al.*, 2000), so the sample deemphasized other land types that might be nutrient source areas (such as developed land). Also, the model does not account for point sources associated with other land types. Therefore, we focus on interpreting the model for sources and fates of cropland nitrate.

We also integrated the analysis units within each province to summarize the differences among provinces. Total cropland losses from the CP and PD are roughly equal when summarized as either concentrations or yields (Figure 6, left and middle). The CP (17.5% cropland) has about three times the cropland as the PD (5.6%, Figure 2), but this difference is offset by cropland releases in the PD (32.3) that are roughly three times the cropland releases in the CP (10.7, Table 2).

When contrasting among provinces, total cropland losses for the Appalachian provinces are relatively larger in the yield plot than in the concentration plot. The changes in pattern among provinces between the concentration summary and the yield summary reflect the progressively increasing water yields across the sequence (CP < PD < AM < AP, Figure 5). In the load summary, the AM province becomes even larger relative to other provinces because it comprises a much larger part of the Chesapeake watershed (Figure 2, inset) and produces more stream water (Figure 5, left) than the other provinces.

Compared to the other provinces, the CP has much higher removal by buffers (46% of cropland load, Figure 6, center) and a much higher potential for additional removal from buffer restoration in cropland buffer gaps (another 47% of cropland load). Only 6% of the CP cropland load is not controllable with buffers. In contrast, 69% of the cropland load in the PD is not controllable with buffers, while existing and possible restoration removal (11 and 21%, respectively, of cropland load) are much less in the PD than in the CP. The two Appalachian provinces are intermediate between CP and the PD.

The CP provides more than half (52%) of buffer reduction of Bay-wide nitrate loads and the largest proportion (36%) among the four provinces of potential additional removal from buffer restoration in cropland buffer gaps (Figure 6, right).

Maps of the nitrate yield components for the hydrologic units show details lost in the province summaries (Figure 6) and reveal differences in nitrate sources and removal by buffers within provinces (Figure 7). Tables S3-S5 provide numerical data for the information summarized in Figures 6 and 7.

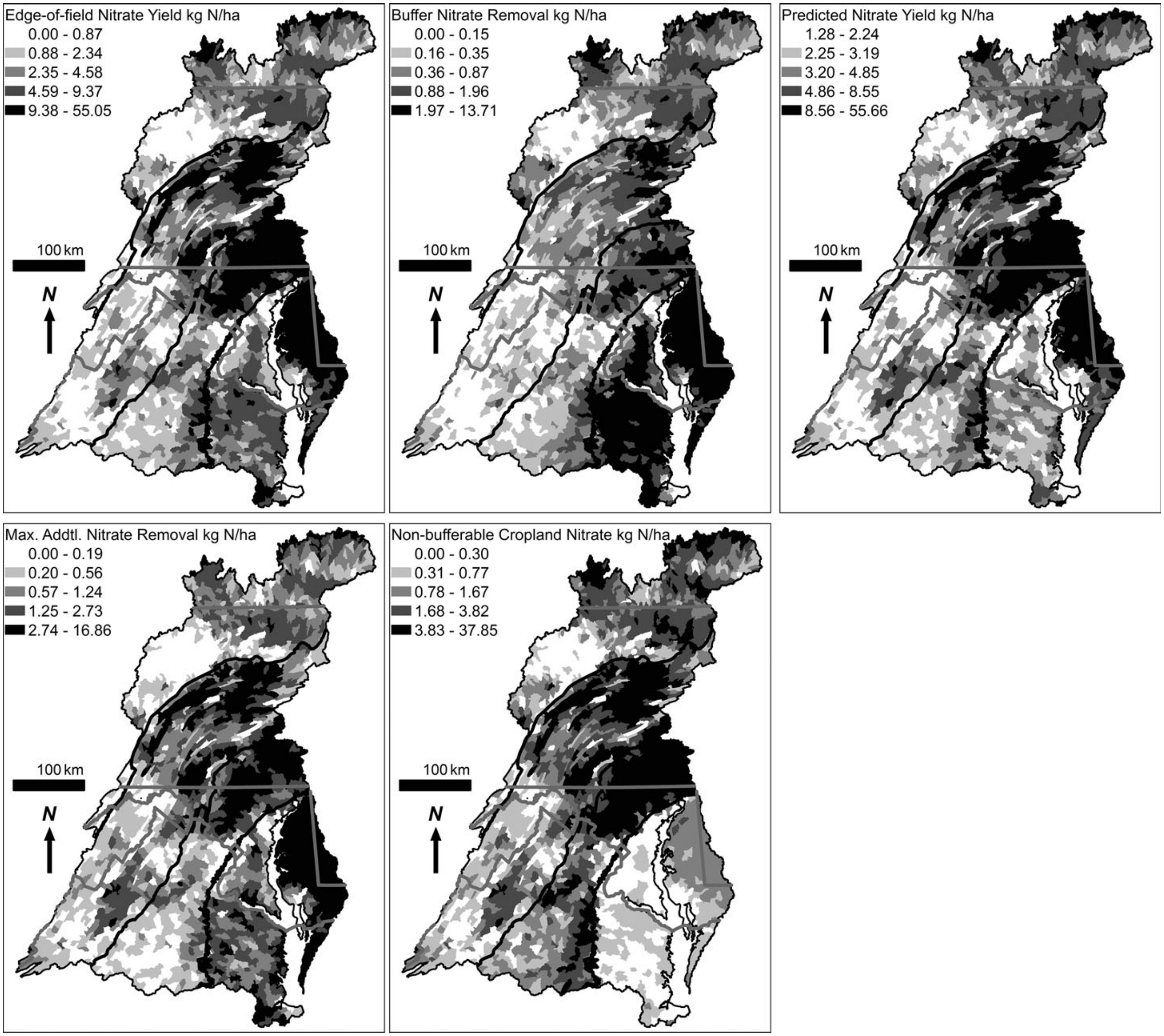

FIGURE 7. Maps of the Components of Stream Nitrate Yield for the Hydrologic Units (in kg N per hectare of watershed). Top left, nitrate originating in cropland ($N_1 + N_2 + N_3 + N_4$); top center, removal in existing buffers (N_4); top right, existing level of stream nitrate ($N_0 + N_1 + N_2 + N_3$); bottom left; possible removal by buffers restored in cropland buffer gaps (N_3); bottom center, cropland nitrate not controllable with buffers ($N_1 + N_2$).

Uncertainties

We used bootstrapping to estimate uncertainties (95% confidence limits) for all predicted quantities. The confidence limits for streamflow were narrow: ±3.06% for both the 46.1 cm average water yield and the 75.6 Gm^3 total stream volume (Figure 5). The narrow confidence limits reflect the very high explanatory power of the flow model (R^2 = 0.994, Vogel *et al.*, 1999). Compared to the flow model, prediction uncertainty for the nitrate concentration model was more than twice as high (±7.41% for 1.29 mg/l average nitrate concentration for the entire Chesapeake watershed). The higher uncertainty is consistent with lower explanatory power of the nitrate model (R^2 = 0.76).

Prediction uncertainties for nitrate yield or load were only slightly larger than the prediction uncertainties for nitrate concentration. For example, for the whole Chesapeake watershed, the uncertainty is ±8.05% for both the 5.96 kg N/ha average nitrate yield to streams (Figure 8) or the 97.6 Gg N average

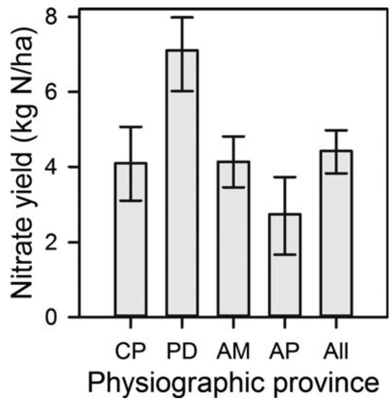

FIGURE 8. Province Average Values for Predicted Existing Stream Nitrate Yields (kg N/ha) with 95% Confidence Limits from Bootstrapping. Relative percentage errors represented by the province confidence limits are ±17%, ±10%, ±13%, ±22%, and± 8% for CP, PD, AM, AP, and entire watershed, respectively. The provinces are the Coastal Plain (CP), Piedmont (PD), Appalachian Mountain (AM), and Appalachian Plateau (AP).

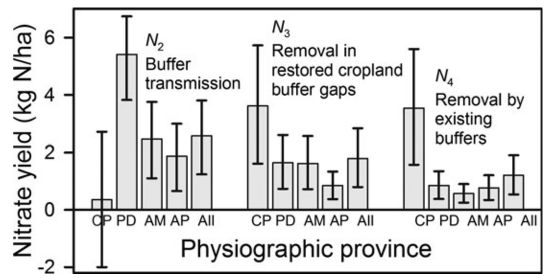

FIGURE 9. Province Average Values for Predicted Components of Cropland Stream Nitrate Yields (kg N/ha) with 95% Confidence Limits from Bootstrapping. Relative percent errors for components are ±57% for all N_3 and N_4 components. Relative errors for N_2 components differ among provinces (±662%, ±27%, ±54%, ±63%, and ±50% for CP, PD, AM, AP, and entire watershed, respectively). N_1 values (data not shown) are all very low (≤0.12 kg N/ha) and all have ±45% relative error. The provinces are the Coastal Plain (CP), Piedmont (PD), Appalachian Mountain (AM), and Appalachian Plateau (AP).

load to streams. Uncertainties are slightly higher for nitrate yields or loads than for concentrations because of the additional uncertainty in the flow predictions, but the increase is very small (from ±7.41% for watershed-wide average nitrate concentration to +8.05% for average nitrate yield). Most of the uncertainty in the nitrate yields or loads comes from the nitrate model rather than the flow model, again consistent with the lower explanatory power of the nitrate model compared to the flow model. Across all the predictions of nitrate yields or loads and their sums (Table 1), prediction uncertainties for nitrate yields or loads are at most 1% higher than those for nitrate concentration (Tables S3-S5).

There were important differences in prediction uncertainty among the nitrate components considered. Predictions of existing stream nitrate levels were the most precise. The confidence limits for stream nitrate yield were ±8% across the entire watershed and ±10-22% for individual provinces (Figure 8). The nitrate model is calibrated with data on stream nitrate levels, so those levels can be predicted with relatively high confidence. Estimating other nitrate components requires using model coefficients to calculate quantities for which no calibration data are available, so those estimates are inherently more uncertain than estimates of stream levels.

The uncertainty in any predicted nitrate component (Figure 9, Tables S3-S5) reflects the uncertainties in the nitrate model coefficients that are used to estimate that quantity. Quantities that depend on a single model coefficient have the same relative error as that coefficient. For example, nitrate components N_0, N_1, and $N_0 + N_1$ depend only on coefficient β_0 (Table A1). Those components and β_0 all have 45% relative error for every province and for the entire watershed (Table 2, Figure 9). Similarly, N_3, N_4, and $N_3 + N_4$ depend only on β_u (Table A1), and all have 57% relative error.

The uncertainty in estimating component N_2 differs among provinces because N_2 depends on model coefficients β_c, which have different values for different provinces (Table 2). The CP value of N_2 has a very high relative uncertainty (±662%) matching the uncertainty of coefficient β_c for the CP (Table 2). N_2 for the other provinces have more moderate uncertainties (±27-62%) matching the relevant province coefficients (Table 2). The confidence interval for N_2 in the CP is roughly twice as wide as for the other provinces (Figure 9), but relative error increases substantially when the confidence interval is divided by the very low CP estimate of N_2 (0.12 kg N/ha).

We have summarized the uncertainties for nitrate yield above, but the same patterns apply to nitrate concentration and nitrate load. Numerical information on the estimates and uncertainties for concentrations, yield, and loads as well as uncertainties for all quantities (including those that depend on more than one model coefficient) are detailed in Tables S3-S5.

DISCUSSION

Buffer Effects throughout the Chesapeake Bay Watershed

This analysis is the first to use empirical models to quantify the impact of riparian buffers on cropland pollutant loads across the entire Chesapeake Bay (or any other large watershed).

We adapted our earlier approach (Weller *et al.*, 2011), which overcame limitations in spatial analysis and statistical modeling that have long confounded statistical modeling of riparian buffer effects on watershed nutrient discharges. Our published analysis incorporated spatially explicit buffer metrics that account for the disposition of riparian buffers along the flow paths that connect croplands to streams (Baker *et al.*, 2006b), plus improved statistical models that provide more discerning tests of buffer effects and direct estimates of nitrate removal in buffers (Weller *et al.*, 2011). However, our previous analysis was implemented for a sample of study watersheds that comprise less than 8% of the Chesapeake Bay drainage and represented only three of the four major physiographic provinces (omitting the AP). This study extends the flow-path analysis of buffer prevalence to describe the entire Chesapeake watershed, recalibrates the nitrate model with data from all four major physiographic provinces, and incorporates accurate and precise streamflow predictions (Vogel *et al.*, 1999) to estimate stream nitrate yields and loads as well as concentrations. Concentrations are valuable for understanding effects in local stream system, but load estimates are essential for understanding likely impacts on the Chesapeake Bay.

The watershed-wide spatial analysis found that cropland occupies 6.7% of the Chesapeake Bay watershed, and 41% of that cropland is connected to a buffer detectable with the NLCD land cover data (Figures 2 and 3). Among the physiographic provinces, the CP has the highest cropland proportion (17.5%) and the prevalence of buffers (50% of cropland buffered). Compared to the CP, cropland proportions are lower in the other three provinces and buffer prevalence is lower in the PD and AM provinces.

Across the entire Chesapeake watershed, we estimate that circa 1990 croplands released 92.3 Gg of nitrate nitrogen, and the 95% confidence interval for that release (expressed as percent relative error) is ±14% (Figure 6, Tables S5). Riparian buffers removed 22% of that cropland load (19.8 Gg, relative confidence ±57%) so that only 72.5 Gg (±13%) was delivered to streams. At most, another 24% of the cropland release (29.4 Gg, ±57%) might have been removed through a buffer restoration that addressed all cropland runoff. The remainder of cropland load (43.1 Gg, ±50%) cannot be reduced with riparian buffers and must be addressed by other management practices. The CP province provided more than half (52%) of the nitrate removal by buffers for the entire watershed and the largest proportion (36%) of the maximum additional nitrate removal from buffer restoration in cropland buffer gaps. This reflects the high prevalence of cropland on the CP and the higher relative removal efficiency of CP buffers (Table 3).

The 29.4 Gg estimate of additional nitrate removal from buffer restoration in cropland buffer gaps should be considered an upper limit because restored buffers may not perform as well as existing buffers. Buffers are often remnant forest or wetlands in wet areas that may be better sites for nitrate removal than previously cleared areas available for restoration. Restored buffers may also take some time to develop nitrate removal capacities (Gregory *et al.*, 2007; Vidon *et al.*, 2014). Weller *et al.* (2011) provide more information and citations on the possible limits on additional nitrate removal in restored buffers.

The model coefficient values of the expanded nitrate model (Table 2) are very similar to those of our previous model (Table 3) (Weller *et al.*, 2011). The predicted province average stream nitrate levels are more distinct between the two analyses than the coefficients (compare Figure 7 here with figure 6 in Weller *et al.*, 2011) because the complete spatial analysis of land cover throughout the entire Chesapeake Bay watershed (Figures 2 and 3) provides more accurate estimates of the prevalence of cropland and riparian buffers than did the study watershed sample (figure 3 in Weller *et al.*, 2011). For example, the sampled PD watersheds showed greater potential removal in buffers restored in cropland buffer gaps than the sampled CP watersheds (Weller *et al.*, 2011), but the complete analysis shows the CP has more removal by existing buffers and more possible removal from restoring buffers in cropland buffer gaps than the PD (Figure 6). The sample deliberately included watersheds with unusually high amounts of cropland to better calibrate models relating stream nutrient levels to agricultural land use (Liu *et al.*, 2000; Weller *et al.*, 2011). The geographic description in the present analysis (Figures 2 and 3) avoids sampling bias by analyzing the entire watershed rather than relying on a sample.

The present analysis extended our previous work by using bootstrapping to estimate uncertainties for all quantities considered. The estimates of water discharges are very precise (Figure 5), and the relative uncertainties of existing stream nitrate levels (±10-22% for provinces, ±8% watershed wide, Figure 8) are also low in comparison to other watershed models (e.g., Ator *et al.*, 2011; Boomer *et al.*, 2013). The percent relative errors for estimating nitrate components (such as existing buffer nitrate removal or possible removal from restoring buffers in cropland buffer gaps) are much larger than for matching stream levels (Figure 9). It is much easier for the model to reproduce stream levels, for which calibration data are available, than to precisely separate nitrate sources and sinks, for which calibration data are not available.

Comparison to Other Chesapeake Watershed Nitrogen Models

We compared our analysis to other Chesapeake watershed models that account for cropland nitrogen discharge. The USDA Conservation Effects Assessment Program (CEAP) examined the effects of croplands and various agricultural conservation practices on nitrogen and phosphorus loads to Chesapeake Bay (USDA-NRCS, 2011). The USDA reported that 10.5% of the Chesapeake Bay watershed is cultivated cropland, and that only 10% of that cropland is treated with some kind of edge-of-field buffering by grass filter strips or by herbaceous or forested riparian buffers (table 6 in USDA-NRCS, 2011). This estimate is much lower than our calculation that 42% of Chesapeake Bay cropland is buffered by a riparian forest or wetland wide enough to be detectable using NLCD land cover (30-m^2 pixels). We suspect that the CEAP emphasis on "edge-of-field buffering" may miss streamside buffers that we observed along crop-to-stream flow paths at some distance from the edges of fields.

The Phase 5 version of the Chesapeake Bay Program (CBP) Watershed Model has been used to set TMDL limits for watershed-wide inputs of nitrogen, phosphorus, and sediment to Chesapeake Bay (USEPA, 2010b, c). The CBP model reports that cropland occupies 8.1% of the Chesapeake watershed (USEPA, 2010a). The model considers riparian buffers, but only those buffers that have been added as new management practices. Natural buffers present before 1992 are not considered (USEPA, 2010a). The model includes no spatial analysis to connect source areas through buffers to streams, but instead makes the arbitrary assumption that a unit of riparian forest always treats the discharges from four units of source land (USEPA, 2010a). Water yield from the CBP simulation model closely agreed with our estimate. For the years 1985-2000, the CBP predicted an average of 76.8 Gm^3/year of water delivered to the Bay (74.6 Gm^3/year without point source discharges). Either number is within the 95% confidence limits for our estimate of 75.6 Gm^3/year (95% CI [73.4, 78.0]).

The U.S. Geological Survey has applied its SPARROW statistical model to quantify the sources of nitrogen and phosphorus within the Chesapeake watershed and to estimate their delivery to the Bay (Ator *et al.*, 2011). The model does not account for the distribution of riparian buffers and does not account for buffer nitrogen removal. Nonetheless, the spatial patterns in our map of stream nitrate yield (Figure 7) closely matches the pattern in the SPARROW maps of fertilizer and manure nitrogen yields entering the stream network from the land (figure 9 in Ator *et al.*, 2011). This close agreement is not surprising — both models are statistical models calibrated with large datasets of stream nitrogen measurements spread across the watershed.

It is more difficult to compare our nitrate-nitrogen loads to the numbers predicted by the other Chesapeake watershed models. We focused on the nitrate-nitrogen loads to streams for two reasons. Nitrate is by far the dominant form of nitrogen lost from croplands (Jordan *et al.*, 1997c), and nitrate is cheaper and easier to measure in streams than other forms of nitrogen (Weller *et al.*, 2010). The CBP and USDA models are capable of predicting nitrate load to streams, but those predictions were not included in available reports, which focus on total nitrogen loads delivered to larger rivers or to the Bay itself. The SPARROW model predicts total nitrogen loads to streams, and the spatial patterns of those loads are quite similar to patterns in our nitrate load (see above).

We recommend that other models incorporate riparian buffers more explicitly. Models that ignore cropland buffers can work well for reproducing stream levels because cropland proportions and buffer prevalence are often correlated (Baker *et al.*, 2006b; Weller *et al.*, 2011). However, ignoring buffers fosters misleading inferences, and models without buffers are not adequate for understanding and interpreting the sources and fates of nutrients. For example, in this Chesapeake-wide analysis, we estimated that croplands released 92.3 Gg of nitrate N and 19.8 Gg of that was removed in riparian buffers so that only 72.5 Gg of cropland nitrate N reached streams, along with 25.1 Gg from other land covers. If we omit buffers from the nitrate model (e.g., the LP model in Weller *et al.*, 2011) and recalculate loads, then we would estimate that croplands release 79.2 Gg of nitrate nitrogen, all of that is delivered to streams (no removal by riparian buffers), and 16.0 Gg comes from other land covers. Omitting buffers reduced the estimate of edge-of-field cropland loss by almost 15% and also lowered the load from other land covers by 30%. Omitting buffers greatly changes our assessments of losses from cropland, losses from other land covers, and buffer effects, but does not much change the estimate of stream load. This simple example illustrates how not accounting for buffers may disrupt the calibrations of other models and their attributions of nutrient sources and fates. Including buffers in other Chesapeake watershed models should improve explanatory power (e.g., higher R^2) and provide more reliable interpretations of nutrient sources and fates. Currently, none of the other Chesapeake models quantify existing buffer benefits or the potential for buffer restoration. Such information is essential for conservation and planning efforts (STAC, 2012). A toolbox for ArcGIS is available (http://ches.

communitymodeling.org/models.php#buffer) to implement our flow-path calculations (Baker *et al.*, 2006b; Weller *et al.*, 2011) for other analyses.

Directions for Further Research

Our earlier analysis of selected study watersheds identified several enhancements that would improve watershed models of riparian buffer effects on stream nitrate levels. The enhancements included: more accurately classified land cover to better identify croplands, forests, and wetlands; higher resolution land cover; improved description of subsurface flow connectivity from croplands to streams; more stream nitrate samples; random sampling of stream nitrate levels; and incorporating indicators of nitrate removal potential, such as topographic estimates of local wetness. We emphasize that Landsat-based land cover data (like the NLCD 1992 data used here, Vogelmann *et al.*, 1998a, b) have 30 m × 30 m pixels and can only quantify buffer prevalence along flow paths at the presence/absence level (Weller *et al.*, 2011). Despite this limitation, Landsat still provides the best resolution data available for Chesapeake-wide analysis. When higher resolution land cover data become available, our analysis should be repeated to detect and incorporate narrow buffers and to model the effects of buffer width as well as buffer presence. Our previous study provides details and citations to possible approaches to the other suggested improvements listed above (Weller *et al.*, 2011).

The present wall-to-wall analysis of the Chesapeake watershed supports the need for these improvements and suggests an additional need to consider within-province variability in nitrate source and removal potentials. The geographic analysis already accounts for differences in cropland and buffer prevalence both among and within provinces (Figures 2 and 3), but we have only one set of nitrate model coefficients for each entire province. Evidence from the CP and PD suggests that the model should consider smaller regions in each province. The 95% relative removal estimate for the CP seems quite high, but it is also fairly uncertain (Table 3). The uncertainties of CP nitrate components (particularly N_2 the nitrate load that would reach streams if all cropland were buffered), are much higher than for the other provinces (Figure 9).

Some of the uncertainty in modeling the CP arises because shallow regression slopes (like the CP coefficient β_c, Table 2) are difficult to fit and tend to regress toward zero with noisy data (Sokal and Rohlf, 1981). In addition, although CP studies provide some of the best documented examples of high buffer nitrogen removal (Lowrance *et al.*, 1997), other studies of particular CP regions have concluded that riparian buffers remove little cropland nitrogen because subsurface flow paths in those regions do not move cropland discharges thorough buffers (Denver, 1991; Bohlke and Denver, 1995; Speiran, 2010). As more nitrate measurements become available, such differences could be incorporated into our model by fitting separate coefficients for different sections of the CP with different subsurface characteristics (Shedlock *et al.*, 1999). Incorporating information on subsurface flow paths into the spatial analysis of buffer prevalence could also improve model performance and interpretation (Gerla, 1999; Baker *et al.*, 2001; Kellogg *et al.*, 2008).

SUMMARY AND CONCLUSIONS

Our previous geographic and statistical analyses resolved long-standing problems in modeling riparian buffer effects and quantified the effects of croplands, existing buffers, and possible buffer restoration on stream nitrate concentrations for a set of selected study watersheds (Baker *et al.*, 2006b; Weller *et al.*, 2011). In this study, we extended that work to the entire Chesapeake Bay watershed. We applied flow-path analysis to quantify cropland and buffer prevalence throughout the entire watershed, extended the calibration of the nitrate concentration model from three to all four major physiographic provinces by adding calibration watersheds for the AP, implemented a very accurate model of average annual stream discharge to convert concentration predictions to yield and loads, and applied bootstrapping to estimate uncertainties for all model coefficients, model predictions, and spatial summaries of those predictions. This analysis is the first to use empirical models to quantify the impact of riparian buffers on cropland pollutant loads across the entire Chesapeake Bay (or for any other large watershed).

Key findings include:

1. Cropland is 6.7% of the Chesapeake Bay watershed in the circa 1990 NLCD land cover.
2. 41% of the cropland is buffered by riparian forest or wetland detectable with NLCD.
3. The CP has the highest cropland (17.5%) and prevalence of riparian buffers (50% of cropland buffered) among provinces.
4. Buffer prevalence is lower in the PD and AM provinces.
5. Croplands release 92.3 Gg (% relative error ±14%) of nitrate-nitrogen watershed wide.

6. Riparian buffers remove 22% of the cropland load (19.8 Gg, ±57%).
7. 72.5 Gg (±13%) of the cropland load of nitrate nitrogen reaches streams.
8. Another 32% of the cropland load (29.4 Gg, ±57%) might be removed after restoring buffers in all cropland buffer gaps.
9. 32% is an upper limit because restored buffers may not remove as much nitrate as existing buffers.
10. 46% of cropland load (42.1 Gg, ±50%) cannot be reduced with riparian buffers.
11. That 46% must be addressed by using less nitrogen or by other management practices.
12. Opportunities and benefits of restoration vary among and within provinces.
13. The CP province provides 52% of the existing nitrate removal.
14. The CP offers the largest fraction (36%) of the maximum additional nitrate removal from restoring buffers in all cropland buffer gaps.
15. Other provinces still offer substantial opportunities for buffer restoration that would remove additional nitrate.
16. The uncertainty for predicting nitrate loads is much higher than for predicting water discharge.
17. The uncertainty for attributing nitrate sources and sinks is greater than for matching stream nitrate levels.

APPENDIX

MODEL SPECIFICATION AND CALCULATING NITRATE COMPONENTS

The parsimonious buffer effects (BFp) model is given by the equation:

$$
\begin{aligned}
N = & \underbrace{\beta_0 + \beta_{0p}P_p + \beta_{0a}P_a}_{\text{background}} \\
& + \underbrace{(\beta_c + \beta_{cp}P_p + \beta_{ca}P_a + \beta_{ch}P_h)C}_{\text{cropland}} \\
& + \underbrace{\beta_u C_u}_{\text{unbuffered cropland}} + \varepsilon,
\end{aligned} \tag{A1}
$$

where N is nitrate concentration; C and C_u are the proportions of cropland and unbuffered cropland, β values are fitted model coefficients; ε is error; and P_p, P_a, and P_h are dummy variables representing the categorical variable physiographic province. $P_p = 1$ for the Piedmont province and zero otherwise, $P_a = 1$ for the Appalachian Mountain province and zero otherwise, and $P_h = 1$ for the Appalachian Plateau province and zero otherwise. For the Coastal Plain, P_p, P_a, and P_h are all zero. The first subscript on a coefficient β represents the land cover to which that coefficient applies (c for cropland or u for unbuffered cropland). If present, the second subscript represents the dummy variable for physiographic province to which the coefficient applies (p, a, or h for P_p, P_a, or P_h). We used the "lm" function of the R statistical package (R Core Team, 2012) to fit the models.

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Figure S1. Circa 1990 land cover for the Chesapeake Bay watershed.

Figure S2. Average annual precipitation and temperature for hydrologic units of the Chesapeake Bay watershed.

Figure S3. Nitrate concentration, yield, and load predicted for hydrologic units of the Chesapeake Bay watershed.

TABLE A1. Calculating the Components of Stream Nitrate Using the Nitrate Concentration Model.

Nitrate Component Sources of Nitrate to Stream Water	Symbol	Physiographic Province CP	PD	AM	AP
Other land covers	N_0	$\beta_0 (1 - C)$			
Background from cropland	N_1	$\beta_0 C$			
Buffer transmission	N_2	$\beta_c C$	$(\beta_c + \beta_{cp}) C$	$(\beta_c + \beta_{ca}) C$	$(\beta_c + \beta_{ch}) C$
Possible removal in restored buffer gaps	N_3	$\beta_u C_u$			
Removal by existing buffers	N_4	$\beta_u C_b$			

Notes: Model variables and coefficients are as defined in the Appendix text. Other quantities of interest can be calculated by adding subsets of component N_0-N_4 (see Table 1). The provinces are the Coastal Plain (CP), Piedmont (PD), Appalachian Mountain (AM), and Appalachian Plateau (AP).

Table S1. Prevalence of cropland and riparian buffers in the Chesapeake Bay watershed.

Table S2. Model performance for five models predicting stream nitrate concentration based on land cover proportions and physiographic province.

Table S3. Province averages for predicted components of mean annual stream nitrate concentration with confidence limits and relative uncertainties.

Table S4. Province averages for predicted components of annual stream nitrate yield and stream discharge with confidence limits and relative uncertainties.

Table S5. Province sums for predicted annual nitrate loads and stream discharge volume with confidence limits and relative uncertainties.

Table S6. Glossary of terms, variables, and formulas.

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Supporting Information

CROPLAND RIPARIAN BUFFERS THROUGHOUT CHESAPEAKE BAY WATERSHED: SPATIAL PATTERNS AND EFFECTS ON NITRATE LOADS DELIVERED TO STREAMS

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Note: Citations in the Supporting Information refer to the Literature Cited section in the paper.

FIGURE S1. Circa 1990 land cover for the Chesapeake Bay watershed ("NLCD 1992" Vogelmann *et al.*, 1998a, b; USEPA, 2007).

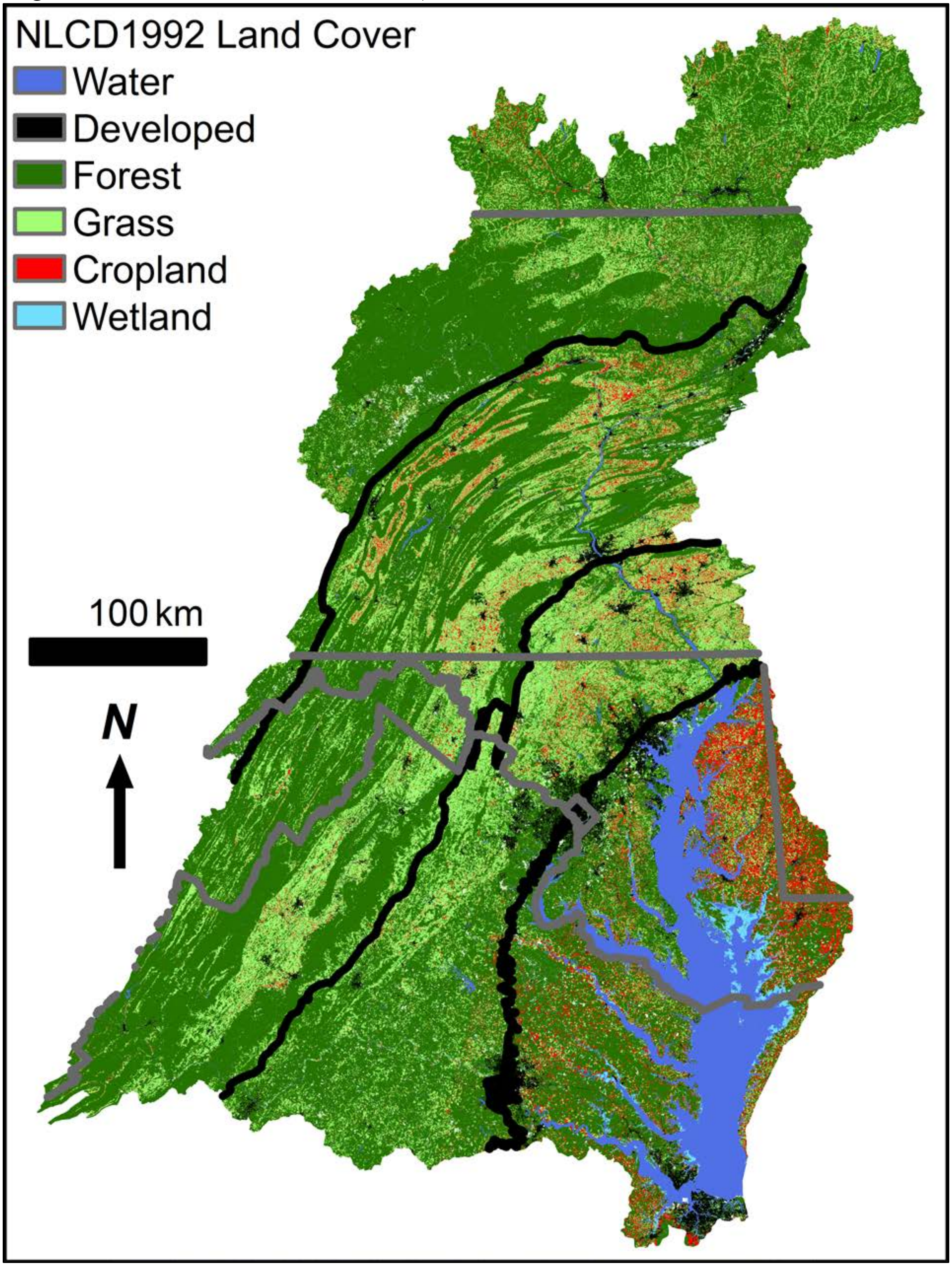

FIGURE S2. Average annual precipitation and temperature for hydrologic units of the Chesapeake Bay watershed. Data are 1971-2000 “800 m annual climatology normals” from the PRISM climate data (Daly *et al.*, 2002; PRISM, 2007).

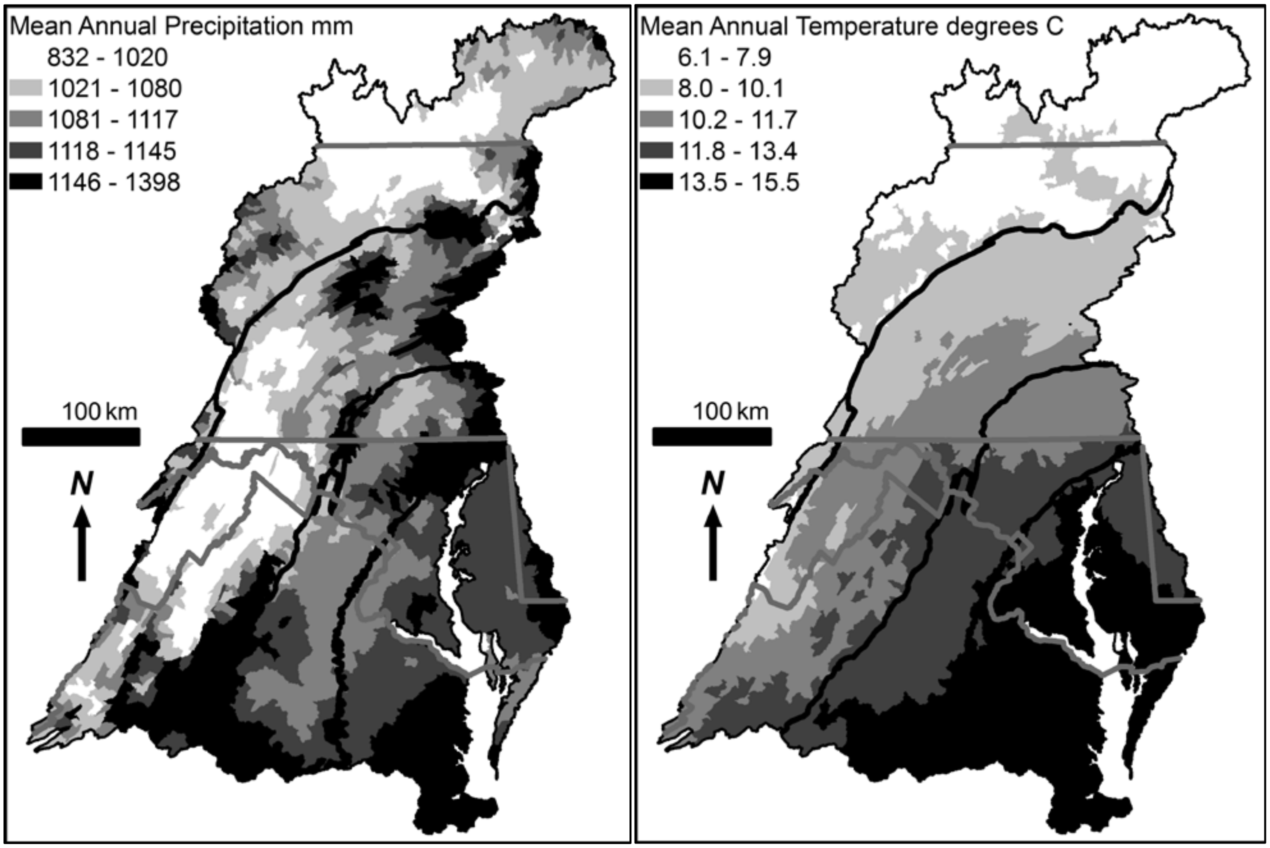

FIGURE S3. Nitrate concentration, yield, and load for hydrologic units of the Chesapeake Bay watershed. All panels show predicted existing stream nitrate levels (N_0+N_1+N_2+N_3), but in different units.

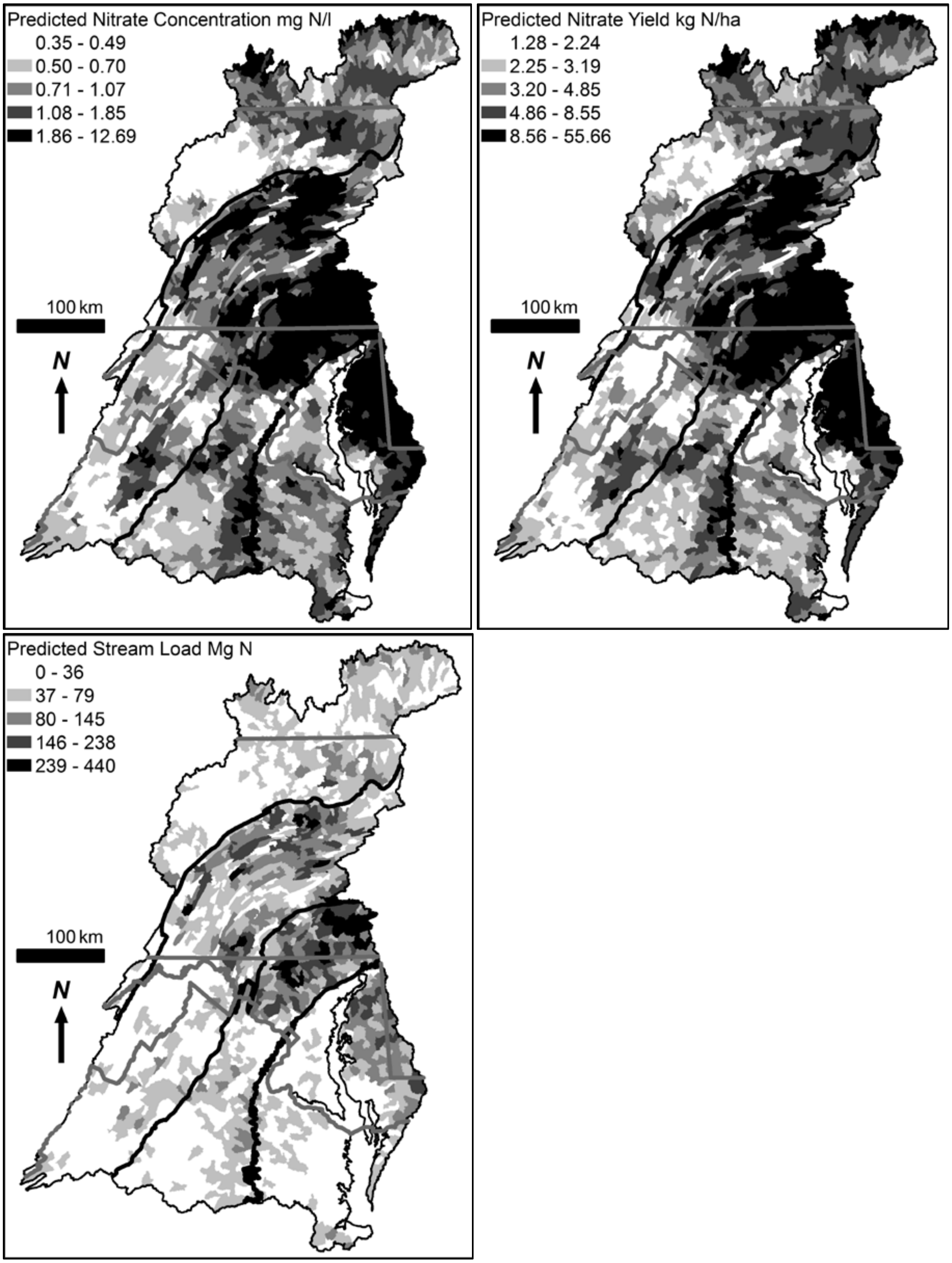

TABLE S1. Prevalence of cropland and riparian buffers in the Chesapeake Bay watershed.

Physiographic Province	Land Area (km^2)	Cropland Proportion C	Cropland Buffer Gap Fraction $FGAP_c$	Unbuffered Cropland C_u	Buffered Cropland C_b
Coastal Plain	29,277	0.175	0.504	0.088	0.087
Piedmont	35,064	0.056	0.655	0.036	0.019
Appalachian Mountain	59,469	0.045	0.748	0.034	0.011
Appalachian Plateau	40,120	0.030	0.527	0.016	0.014
Entire Watershed	163,930	0.067	0.593	0.040	0.027

Notes: Land area excludes water. Cropland is expressed as the proportion of land area in the watershed, and $FGAP_c$ is unbuffered cropland area relative to total cropland area.

TABLE S2. Model performance for five models predicting stream nitrate concentration based on land cover proportions and physiographic province.

Model	r^2	K	AIC_c	Δ	Akaike Weight w_i
LP	0.744	11	159	31	0
LPp	0.741	9	158	29	0
BF	0.762	15	144	15	0
BFp	0.756	7	128	0	0.94
BFp+	0.758	10	134	6	0.06

Notes: The BF, BFp, and BFp+ models account for riparian buffers, while the LP and LPp models do not (Weller *et al.*, 2011). Weller *et al*. also provide more details on model formulation and the interpretation of the information theoretic measures of model comparison (Δ and Akaike weight w_i; see Burnham and Anderson, 2002). K is the number of model parameters estimated (including model residual error).

TABLE S3. Province averages for predicted components of mean annual stream nitrate concentration (in mg N/l) with confidence limits and relative uncertainties.

Nitrate Component	Symbol	Coastal Plain	Piedmont	Appalachian Mountain	Appalachian Plateau	All
Sources of nitrate to stream water						
Other land covers	N_0	0.31 [0.18 , 0.46] *45*	0.33 [0.19 , 0.49] *45*	0.33 [0.19 , 0.49] *45*	0.34 [0.20 , 0.50] *45*	0.33 [0.19 , 0.49] *45*
Background from cropland	N_1	0.03 [0.02 , 0.05] *45*	0.01 [0.01 , 0.02] *45*	0.01 [0.01 , 0.02] *45*	0.01 [0.00 , 0.01] *45*	0.01 [0.01 , 0.02] *45*
Buffer transmission	N_2	0.09 [-0.51 , 0.68] *662*	1.28 [0.91 , 1.58] *27*	0.53 [0.24 , 0.81] *53*	0.34 [0.12 , 0.55] *62*	0.56 [0.27 , 0.82] *50*
Possible removal in restored buffer gaps	N_3	0.91 [0.40 , 1.45] *57*	0.39 [0.17 , 0.62] *57*	0.35 [0.16 , 0.55] *57*	0.16 [0.07 , 0.25] *57*	0.39 [0.17 , 0.61] *57*
Removal by existing buffers	N_4	0.89 [0.39 , 1.41] *57*	0.20 [0.09 , 0.32] *57*	0.12 [0.05 , 0.19] *57*	0.14 [0.06 , 0.22] *57*	0.26 [0.12 , 0.41] *57*
Sums of cropland nitrate components						
Originating in cropland	$N_1+N_2+N_3+N_4$	1.93 [1.38 , 2.49] *29*	1.88 [1.61 , 2.09] *13*	1.02 [0.88 , 1.15] *13*	0.65 [0.44 , 0.84] *31*	1.22 [1.05 , 1.38] *14*
Due to cropping activity	$N_2+N_3+N_4$	1.90 [1.35 , 2.45] *29*	1.87 [1.60 , 2.07] *13*	1.01 [0.87 , 1.14] *14*	0.64 [0.44 , 0.84] *31*	1.21 [1.03 , 1.37] *14*
Non controllable by buffers	N_1+N_2	0.12 [-0.47 , 0.71] *487*	1.29 [0.92 , 1.59] *26*	0.54 [0.26 , 0.82] *52*	0.35 [0.13 , 0.55] *61*	0.57 [0.29 , 0.83] *48*
Controllable by buffers	N_3+N_4	1.81 [0.80 , 2.86] *57*	0.59 [0.26 , 0.93] *57*	0.47 [0.21 , 0.75] *57*	0.30 [0.13 , 0.47] *57*	0.65 [0.29 , 1.03] *57*
Cropland contribution to stream nitrate under different scenarios						
With no crops	N_1	0.03 [0.02 , 0.05] *45*	0.01 [0.01 , 0.02] *45*	0.01 [0.01 , 0.02] *45*	0.01 [0.00 , 0.01] *45*	0.01 [0.01 , 0.02] *45*
With all buffer gaps restored	N_1+N_2	0.12 [-0.47 , 0.71] *487*	1.29 [0.92 , 1.59] *26*	0.54 [0.26 , 0.82] *52*	0.35 [0.13 , 0.55] *61*	0.57 [0.29 , 0.83] *48*
With existing buffers	$N_1+N_2+N_3$	1.03 [0.78 , 1.27] *24*	1.68 [1.43 , 1.88] *14*	0.89 [0.75 , 1.04] *16*	0.51 [0.31 , 0.69] *37*	0.96 [0.83 , 1.07] *13*
With no buffers	$N_1+N_2+N_3+N_4$	1.93 [1.38 , 2.49] *29*	1.88 [1.61 , 2.09] *13*	1.02 [0.88 , 1.15] *13*	0.65 [0.44 , 0.84] *31*	1.22 [1.05 , 1.38] *14*
Total stream nitrate under different scenarios						
With no crops	N_0+N_1	0.35 [0.20 , 0.51] *45*	0.35 [0.20 , 0.51] *45*	0.35 [0.20 , 0.51] *45*	0.35 [0.20 , 0.51] *45*	0.35 [0.20 , 0.51] *45*
With all buffer gaps restored	$N_0+N_1+N_2$	0.44 [-0.10 , 0.97] *123*	1.62 [1.34 , 1.88] *17*	0.88 [0.63 , 1.13] *28*	0.69 [0.51 , 0.87] *26*	0.90 [0.68 , 1.12] *24*
With existing buffers	$N_0+N_1+N_2+N_3$	1.35 [1.12 , 1.57] *17*	2.01 [1.82 , 2.18] *9*	1.23 [1.08 , 1.39] *12*	0.85 [0.67 , 1.03] *21*	1.29 [1.20 , 1.39] *7*
With no buffers	$N_0+N_1+N_2+N_3+N_4$	2.24 [1.66 , 2.85] *26*	2.21 [1.97 , 2.43] *10*	1.35 [1.19 , 1.53] *13*	0.99 [0.78 , 1.21] *22*	1.55 [1.36 , 1.76] *13*

Notes: Bootstrap 95% confidence limits are in brackets. Numbers in italics are percent relative errors calculated as 100 times half the confidence interval divided by the average.

TABLE S4. Province averages for predicted components of annual stream nitrate yield (kg N/ ha) and stream discharge (cm) with confidence limits and relative uncertainties.

Nitrate Component	Symbol	Coastal Plain	Piedmont	Appalachian Mountain	Appalachian Plateau	All
Stream flow						
Stream Yield cm	Q_{cm}	39.55 [37.86 , 41.39] *4*	42.29 [40.78 , 43.93] *4*	46.23 [44.89 , 47.66] *3*	54.16 [52.20 , 56.17] *4*	46.14 [44.77 , 47.59] *3*
Sources of nitrate to stream water						
Other land covers	N_0	1.24 [0.72 , 1.84] *45*	1.41 [0.81 , 2.08] *45*	1.54 [0.88 , 2.28] *45*	1.84 [1.05 , 2.72] *45*	1.53 [0.88 , 2.26] *45*
Background from cropland	N_1	0.12 [0.07 , 0.18] *45*	0.06 [0.03 , 0.08] *45*	0.05 [0.03 , 0.08] *45*	0.03 [0.02 , 0.04] *45*	0.06 [0.03 , 0.09] *45*
Buffer transmission	N_2	0.36 [-2.00 , 2.71] *662*	5.41 [3.82 , 6.74] *27*	2.46 [1.11 , 3.75] *54*	1.87 [0.65 , 2.99] *63*	2.57 [1.24 , 3.80] *50*
Possible removal in restored buffer gaps	N_3	3.61 [1.61 , 5.73] *57*	1.64 [0.73 , 2.60] *57*	1.62 [0.72 , 2.56] *57*	0.84 [0.38 , 1.33] *57*	1.79 [0.80 , 2.83] *57*
Removal by existing buffers	N_4	3.53 [1.58 , 5.60] *57*	0.85 [0.38 , 1.35] *57*	0.57 [0.25 , 0.90] *57*	0.76 [0.34 , 1.21] *57*	1.21 [0.54 , 1.91] *57*
Sums of cropland nitrate components						
Originating in cropland	$N_1+N_2+N_3+N_4$	7.62 [5.42 , 9.87] *29*	7.96 [6.80 , 8.88] *13*	4.70 [4.07 , 5.35] *14*	3.50 [2.39 , 4.59] *31*	5.63 [4.81 , 6.39] *14*
Due to cropping activity	$N_2+N_3+N_4$	7.50 [5.30 , 9.72] *30*	7.90 [6.73 , 8.83] *13*	4.65 [4.00 , 5.30] *14*	3.48 [2.36 , 4.56] *32*	5.57 [4.74 , 6.33] *14*
Non controllable by buffers	N_1+N_2	0.48 [-1.85 , 2.81] *487*	5.46 [3.90 , 6.78] *26*	2.52 [1.18 , 3.80] *52*	1.90 [0.69 , 3.02] *61*	2.63 [1.32 , 3.84] *48*
Controllable by buffers	N_3+N_4	7.15 [3.19 , 11.33] *57*	2.49 [1.11 , 3.95] *57*	2.19 [0.97 , 3.46] *57*	1.61 [0.72 , 2.54] *57*	3.00 [1.34 , 4.74] *57*
Cropland contribution to stream nitrate under different scenarios						
With no crops	N_1	0.12 [0.07 , 0.18] *45*	0.06 [0.03 , 0.08] *45*	0.05 [0.03 , 0.08] *45*	0.03 [0.02 , 0.04] *45*	0.06 [0.03 , 0.09] *45*
With all buffer gaps restored	N_1+N_2	0.48 [-1.85 , 2.81] *487*	5.46 [3.90 , 6.78] *26*	2.52 [1.18 , 3.80] *52*	1.90 [0.69 , 3.02] *61*	2.63 [1.32 , 3.84] *48*
With existing buffers	$N_1+N_2+N_3$	4.09 [3.10 , 5.06] *24*	7.11 [6.02 , 7.99] *14*	4.14 [3.45 , 4.81] *16*	2.74 [1.67 , 3.72] *38*	4.42 [3.82 , 4.97] *13*
With no buffers	$N_1+N_2+N_3+N_4$	7.62 [5.42 , 9.87] *29*	7.96 [6.80 , 8.88] *13*	4.70 [4.07 , 5.35] *14*	3.50 [2.39 , 4.59] *31*	5.63 [4.81 , 6.39] *14*
Total stream nitrate under different scenarios						
With no crops	N_0+N_1	1.37 [0.79 , 2.02] *45*	1.46 [0.84 , 2.16] *45*	1.60 [0.92 , 2.36] *45*	1.87 [1.07 , 2.76] *45*	1.59 [0.91 , 2.35] *45*
With all buffer gaps restored	$N_0+N_1+N_2$	1.72 [-0.38 , 3.86] *123*	6.87 [5.63 , 7.99] *17*	4.06 [2.93 , 5.23] *28*	3.74 [2.77 , 4.72] *26*	4.16 [3.16 , 5.18] *24*
With existing buffers	$N_0+N_1+N_2+N_3$	5.34 [4.42 , 6.26] *17*	8.51 [7.64 , 9.29] *10*	5.68 [4.99 , 6.43] *13*	4.58 [3.60 , 5.60] *22*	5.96 [5.49 , 6.45] *8*
With no buffers	$N_0+N_1+N_2+N_3+N_4$	8.87 [6.58 , 11.33] *27*	9.36 [8.30 , 10.33] *11*	6.25 [5.48 , 7.10] *13*	5.35 [4.20 , 6.57] *22*	7.16 [6.27 , 8.13] *13*

Notes: Bootstrap 95% confidence limits are in brackets. Numbers in italics are percent relative errors calculated as 100 times half the confidence interval divided by the average. 1 cm of discharge equals 100,000 l/ha.

TABLE S5. Province sums for predicted annual predicted annual nitrate loads (Gg N/yr) and stream discharge volume (Gm^3/yr) with confidence limits and relative uncertainties.

Nitrate Component	Symbol	Coastal Plain	Piedmont	Appalachian Mountain	Appalachian Plateau	All
Stream flow						
Stream Discharge Volume Gm3	Q	11.58 [11.09 , 12.12] *4*	14.83 [14.30 , 15.40] *4*	27.49 [26.70 , 28.34] *3*	21.73 [20.94 , 22.53] *4*	75.63 [73.39 , 78.02] *3*
Sources of nitrate to stream water						
Other land covers	N_0	3.64 [2.09 , 5.38] *45*	4.93 [2.83 , 7.28] *45*	9.18 [5.26 , 13.53] *45*	7.39 [4.23 , 10.91] *45*	25.14 [14.41 , 37.11] *45*
Background from cropland	N_1	0.36 [0.21 , 0.53] *45*	0.19 [0.11 , 0.29] *45*	0.33 [0.19 , 0.48] *45*	0.11 [0.07 , 0.17] *45*	0.99 [0.57 , 1.47] *45*
Buffer transmission	N_2	1.04 [-5.86 , 7.94] *662*	18.96 [13.40 , 23.62] *27*	14.64 [6.58 , 22.30] *54*	7.50 [2.62 , 12.00] *63*	42.14 [20.31 , 62.27] *50*
Possible removal in restored buffer gaps	N_3	10.58 [4.73 , 16.77] *57*	5.76 [2.57 , 9.11] *57*	9.63 [4.29 , 15.23] *57*	3.38 [1.51 , 5.35] *57*	29.35 [13.07 , 46.47] *57*
Removal by existing buffers	N_4	10.34 [4.62 , 16.40] *57*	2.99 [1.33 , 4.73] *57*	3.37 [1.50 , 5.34] *57*	3.07 [1.37 , 4.85] *57*	19.77 [8.82 , 31.29] *57*
Sums of cropland nitrate components						
Originating in cropland	$N_1+N_2+N_3+N_4$	22.32 [15.85 , 28.89] *29*	27.90 [23.83 , 31.12] *13*	27.97 [24.19 , 31.81] *14*	14.06 [9.61 , 18.41] *31*	92.25 [78.89 , 104.83] *14*
Due to cropping activity	$N_2+N_3+N_4$	21.96 [15.51 , 28.47] *30*	27.71 [23.59 , 30.96] *13*	27.64 [23.80 , 31.52] *14*	13.95 [9.48 , 18.31] *32*	91.26 [77.74 , 103.81] *14*
Non controllable by buffers	N_1+N_2	1.40 [-5.41 , 8.23] *487*	19.16 [13.66 , 23.76] *26*	14.96 [7.02 , 22.58] *52*	7.61 [2.77 , 12.10] *61*	43.13 [21.57 , 62.96] *48*
Controllable by buffers	N_3+N_4	20.92 [9.35 , 33.16] *57*	8.75 [3.91 , 13.84] *57*	13.00 [5.79 , 20.58] *57*	6.45 [2.87 , 10.20] *57*	49.12 [21.89 , 77.75] *57*
Cropland contribution to stream nitrate under different scenarios						
With no crops	N_1	0.36 [0.21 , 0.53] *45*	0.19 [0.11 , 0.29] *45*	0.33 [0.19 , 0.48] *45*	0.11 [0.07 , 0.17] *45*	0.99 [0.57 , 1.47] *45*
With all buffer gaps restored	N_1+N_2	1.40 [-5.41 , 8.23] *487*	19.16 [13.66 , 23.76] *26*	14.96 [7.02 , 22.58] *52*	7.61 [2.77 , 12.10] *61*	43.13 [21.57 , 62.96] *48*
With existing buffers	$N_1+N_2+N_3$	11.98 [9.06 , 14.83] *24*	24.91 [21.10 , 28.00] *14*	24.59 [20.52 , 28.60] *16*	10.99 [6.69 , 14.94] *38*	72.48 [62.66 , 81.50] *13*
With no buffers	$N_1+N_2+N_3+N_4$	22.32 [15.85 , 28.89] *29*	27.90 [23.83 , 31.12] *13*	27.97 [24.19 , 31.81] *14*	14.06 [9.61 , 18.41] *31*	92.25 [78.89 , 104.83] *14*
Total stream nitrate under different scenarios						
With no crops	N_0+N_1	4.00 [2.30 , 5.91] *45*	5.12 [2.94 , 7.57] *45*	9.50 [5.45 , 14.01] *45*	7.51 [4.30 , 11.07] *45*	26.14 [14.98 , 38.58] *45*
With all buffer gaps restored	$N_0+N_1+N_2$	5.04 [-1.12 , 11.30] *123*	24.08 [19.76 , 28.00] *17*	24.14 [17.42 , 31.12] *28*	15.01 [11.10 , 18.95] *26*	68.27 [51.78 , 84.98] *24*
With existing buffers	$N_0+N_1+N_2+N_3$	15.62 [12.93 , 18.31] *17*	29.84 [26.79 , 32.59] *10*	33.77 [29.68 , 38.25] *13*	18.39 [14.46 , 22.49] *22*	97.62 [89.99 , 105.71] *8*
With no buffers	$N_0+N_1+N_2+N_3+N_4$	25.97 [19.25 , 33.16] *27*	32.83 [29.10 , 36.21] *11*	37.14 [32.61 , 42.20] *13*	21.45 [16.85 , 26.37] *22*	117.39 [102.75 , 133.34] *13*

Notes: Bootstrap 95% confidence limits are in brackets. Numbers in italics are percent relative errors calculated as 100 times half the confidence interval divided by the province sum.

Table S6. Glossary of terms, variables, and formulas.

Terms	Symbol	Formula
Watershed characteristics		
Watershed land area (km^2) Total land area of a watershed (excluding water, NLCD code 11)	A	
Cropland proportion The proportion of a watershed occupied by cropland (area of NLCD code 82/ total land area)	C	
Cropland buffer gap fraction The fraction of flow paths that originate in cropland and do not pass through a riparian buffer.	FGAP_c	
Unbuffered cropland proportion The proportion of a watershed occupied by unbuffered cropland	C_u	$C\ \mathrm{FGAP}_c$
Buffered cropland proportion	C_b	C-C_u
Nitrate model parameters--all have units of concentration (mg nitrate-nitrogen/l)		
Model intercept Nitrate loss from other land types (besides cropland)	β_0	
Nitrate loss from all cropland Total nitrate loss from buffered cropland Nitrate entering streams from buffered cropland	β_c	
Additional nitrate loss from unbuffered cropland Nitrate removal in buffers	β_u	
Combinations of model parameters		
Total nitrate loss from unbuffered cropland Edge-of-field nitrate loss Nitrate entering streams from unbuffered cropland		$\beta_c + \beta_u$
Relative nitrate removal potential Percent nitrate removal by buffers Buffer efficiency		$100\ \beta_u / (\beta_c + \beta_u)$
Stream discharge model predictions		
Stream water yield (cm); 1 cm=100,000 l/ha	Q_{cm}	
Stream discharge volume (Mm^3 or Gm^3) Stream water yield times watershed area with unit conversions.	Q	$A\ Q_{cm}$
Nitrate components calculated from model parameters and watershed land cover		
N_0-N_4 are first calculated as concentrations (mg N/l); but can be converted to yields (kg N/ha) and then loads (Mg N or GgN)		
by multiplying the concentrations by water yield, Q_{cm}, and then by watershed area, A		
Nitrate loss from other land covers	N_0	β_0 (1-C)
Background Background nitrate loss from cropland Nitrate loss if cropland were converted to another land type Nitrate loss from cropland if cropping activities (tilling, fertilizing, etc.) were stopped	N_1	$\beta_0\ C$
Buffer transmission Crop nitrate reaching streams even if all cropland were buffered	N_2	$\beta_c\ C$
Removal in restored buffers Removal in buffers restored in cropland buffer gaps Maximum additional nitrate removal if buffers were restored in all cropland buffer gaps	N_3	$\beta_u\ C_u$
Removal by existing buffers	N_4	$\beta_u\ C_b$
Sums of cropland nitrate components		
These stream nitrate levels can be expressed as concentrations (mg N/l), yields (kg N/ha), or loads (Mg N or Gg N)		
Nitrate originating in cropland		$N_1+N_2+N_3+N_4$
Nitrate due to cropping activity		$N_2+N_3+N_4$
Cropland nitrate not controllable by buffers		N_1+N_2
Cropland nitrate controllable by buffers		N_3+N_4
Cropland contribution to stream nitrate under different scenarios of cropland and buffers (excludes nitrate from other land types)		
With no crops		N_1
With buffers restored in all cropland buffer gaps		N_1+N_2
With existing buffers		$N_1+N_2+N_3$
With no buffers		$N_1+N_2+N_3+N_4$
Total contribution to stream nitrate under different scenarios of cropland and buffers (includes nitrate from other land types)		
With no crops		N_0+N_1
With buffers restored in all cropland buffer gaps		$N_0+N_1+N_2$
With existing buffers		$N_0+N_1+N_2+N_3$
With no buffers		$N_0+N_1+N_2+N_3+N_4$

Note: Coefficients βc have different values in different physiographic provinces (see Appendix).