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Riparian and Associated Habitat Characteristics Related to Nutrient Concentrations and Biological Responses of Small Streams in Selected Agricultural Areas, United States, 2003–04

Scientific Investigations Report 2009–5224

U.S. Department of the Interior
U.S. Geological Survey

Cover: Photographs of (left) Elm Creek 3.6 miles northwest of Elm Creek, Nebraska, August 6, 2003; and (right) Mira Creek near North Loup, Nebraska, July 28, 2003 (Photographs by M.R. Johnson, U.S. Geological Survey).

Riparian and Associated Habitat Characteristics Related to Nutrient Concentrations and Biological Responses of Small Streams in Selected Agricultural Areas, United States, 2003–04

By Ronald B. Zelt and Mark D. Munn

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U.S. Geological Survey
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Foreword

The U.S. Geological Survey (USGS) is committed to providing the Nation with reliable scientific information that helps to enhance and protect the overall quality of life and that facilitates effective management of water, biological, energy, and mineral resources (http://www.usgs.gov/). Information on the Nation's water resources is critical to ensuring long-term availability of water that is safe for drinking and recreation and is suitable for industry, irrigation, and fish and wildlife. Population growth and increasing demands for water make the availability of that water, measured in terms of quantity and quality, even more essential to the long-term sustainability of our communities and ecosystems.

The USGS implemented the National Water-Quality Assessment (NAWQA) Program in 1991 to support national, regional, State, and local information needs and decisions related to water-quality management and policy (http://water.usgs.gov/nawqa). The NAWQA Program is designed to answer: What is the quality of our Nation's streams and ground water? How are conditions changing over time? How do natural features and human activities affect the quality of streams and ground water, and where are those effects most pronounced? By combining information on water chemistry, physical characteristics, stream habitat, and aquatic life, the NAWQA Program aims to provide science-based insights for current and emerging water issues and priorities. From 1991 to 2001, the NAWQA Program completed interdisciplinary assessments and established a baseline understanding of water-quality conditions in 51 of the Nation's river basins and aquifers, referred to as Study Units (http://water.usgs.gov/nawqa/studyu.html).

National and regional assessments are ongoing in the second decade (2001–2012) of the NAWQA Program as 42 of the 51 Study Units are selectively reassessed. These assessments extend the findings in the Study Units by determining water-quality status and trends at sites that have been consistently monitored for more than a decade, and filling critical gaps in characterizing the quality of surface water and ground water. For example, increased emphasis has been placed on assessing the quality of source water and finished water associated with many of the Nation's largest community water systems. During the second decade, NAWQA is addressing five national priority topics that build an understanding of how natural features and human activities affect water quality, and establish links between sources of contaminants, the transport of those contaminants through the hydrologic system, and the potential effects of contaminants on humans and aquatic ecosystems. Included are studies on the fate of agricultural chemicals, effects of urbanization on stream ecosystems, bioaccumulation of mercury in stream ecosystems, effects of nutrient enrichment on aquatic ecosystems, and transport of contaminants to public-supply wells. In addition, national syntheses of information on pesticides, volatile organic compounds (VOCs), nutrients, trace elements, and aquatic ecology are continuing.

The USGS aims to disseminate credible, timely, and relevant science information to address practical and effective water-resource management and strategies that protect and restore water quality. We hope this NAWQA publication will provide you with insights and information to meet your needs, and will foster increased citizen awareness and involvement in the protection and restoration of our Nation's waters.

The USGS recognizes that a national assessment by a single program cannot address all water-resource issues of interest. External coordination at all levels is critical for cost-effective management, regulation, and conservation of our Nation's water resources. The NAWQA Program, therefore, depends on advice and information from other agencies—Federal, State, regional, interstate, Tribal, and local—as well as nongovernmental organizations, industry, academia, and other stakeholder groups. Your assistance and suggestions are greatly appreciated.

Matthew C. Larsen
Associate Director for Water

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Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square centimeter (cm^2)	0.001076	square foot (ft^2)
square meter (m^2)	10.76	square foot (ft^2)
square centimeter (cm^2)	0.1550	square inch (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
liter (L)	33.82	ounce, fluid (fl. oz)
liter (L)	0.2642	gallon (gal)
milliliter (mL)	0.03382	ounce, fluid (fl. oz)
cubic millimeter (mm^3)	0.00006102	cubic inch (in^3)
	Flow rate	
centimeter per second (cm/s)	0.03281	foot per second (ft/s)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
milligram per square meter (mg/m^2)	0.000003278	ounce, avoirdupois, per square foot (oz/ft^2)
gram per square meter (g/m^2)	0.003278	ounce, avoirdupois, per square foot (oz/ft^2)
	Hydraulic gradient	
meter per kilometer (m/km)	5.27983	foot per mile (ft/mi)
	Energy	
megajoules per square meter per day [(MJ m^{-2} d^{-1})	0.02582	kilowatthour per square foot per day (kWh ft^{-2} d^{-1})

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8×°C)+32.$$

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Abbreviations and Symbols

Abbreviation	Explanation
BioTDB	USGS Biological Transactional Database for NAWQA ecological data
CCYK	Central Columbia Plateau-Yakima River Basin study area, Washington
CNBR	Central Nebraska study area
CV	coefficient of variation, defined as the ratio of the standard deviation to the mean value
DLMV	Delmarva Peninsula study area, Delaware and Maryland
DOQ	digital orthophoto quadrangles
DTH	depositional habitat, an area of organically rich or sandy sediment along stream margins, targeted for biological sampling
GCP	Georgia Coastal Plain study area
GIS	geographic information system
HDAS	NAWQA Habitat Data Analysis System, a component of the BioTDB
LOWESS	locally weighted scatter-plot smooth, a type of local regression method for graphical summary of a bivariate relation
LRL	laboratory reporting level, generally equal to twice the yearly determined long-term method-detection limit
LS	ordinary least squares, a linear regression statistical model-fitting technique
LULC	land use and land cover
LWD	large woody debris
NAWQA	National Water-Quality Assessment Program
NDW	NAWQA Data Warehouse
NEET	topical study of nutrient enrichment effects on stream ecosystems, conducted as part of NAWQA
NHD	National Hydrography Dataset
NLCDe-92	enhanced version of National Land Cover Dataset based on circa-1992 satellite imagery with 30-meter resolution
NWQL	USGS National Water Quality Laboratory, Denver, Colorado
PC	principal component
PCA	principal components analysis, a multivariate exploratory statistical technique
SEE	standard error of estimate, conceptually is a standard deviation of the residual errors about the regression model at any point
USGS	U.S. Geological Survey
WHMI	White-Miami River Basins study area, Indiana and Ohio

Abbreviations and Symbols—Continued

Symbol	Explanation
A_d	drainage area, in km^2
AMp	macrophytes plus macroalgae, percentage cover
B_b	built-up land, total-basin extent, in percent
B_{dnr}	built-up land, drainage-network riparian buffer, in percent
BVC	bank vegetative ground cover, reach mean, in percent
CA_o	open canopy angle, reach mean, in degrees
C_b	cropland and pasture, total-basin extent, in percent
CC_b	extent of bank canopy closure, reach mean, in percent
CC_c	extent of channel canopy closure, reach mean, in percent
C_{dnr}	cropland and pasture, drainage-network riparian buffer, in percent
C_{R25}	cropland land cover, 25-m buffer distance, reach mean, in percent
C_{R50}	cropland land cover, 50-m buffer distance, reach mean, in percent
C_{Rllt}	cropland land cover, longitudinal linear riparian transect, reach mean, in percent
C_{S100}	cropland, 100-m buffer distance, segment mean, in percent
C_{S150}	cropland, 150-m buffer distance, segment mean, in percent
C_{S250}	cropland, 250-m buffer distance, segment mean, in percent
C_{S50}	cropland, 50-m buffer distance, segment mean, in percent
C_{Sllt}	cropland, longitudinal linear riparian transect, segment mean, in percent
$cv.CA_o$	open canopy angle, CV of transect-level measurements, reach level, in percent
$cv.T_{w30}$	water temperature, CV of daily means, 30-day period, in percent
$cv.T_{w60}$	water temperature, CV of daily means, 60-day period, in percent
cv.V	flow velocity, CV of point measurements, reach level, in percent
$cv.W_w$	wetted width, CV of transect-level measurements, reach level, in percent
CvrMp	extent of aquatic macrophyte cover, reach mean, in percent
CvrOv	extent of overhanging vegetation cover, reach level, in percent
CvrUb	extent of undercut bank cover, reach level, in percent
CvrWd	extent of woody debris cover, reach level, in percent
DAFD	ash-free dry mass (organic material), fine-grained benthic habitat, g m^{-2}
DBV	biovolume, fine-grained benthic habitat, mm^3 cm^{-2}
DCD	cell density, fine-grained benthic habitat, 10^6 cells cm^{-2}
DCHL	chlorophyll *a*, fine-grained benthic habitat, mg m^{-2}
DIN	dissolved nitrogen, inorganic, mg/L
D_w	water depth, reach mean, cm
F_b	forest, total-basin extent, in percent
F_{dnr}	forest, drainage-network riparian buffer, in percent
Froude	Froude number, reach mean, dimensionless

Abbreviations and Symbols—Continued

Symbol	Explanation
G_b	grassland, total-basin extent, in percent
G_{dnr}	grassland, drainage-network riparian buffer, in percent
G_{R25}	grassland (managed or unmanaged grass, pasture, or herbaceous rangeland), 25-m buffer distance, reach mean, in percent
G_{S50}	grassland (managed or unmanaged grass, pasture, or herbaceous rangeland), 50-m buffer distance, segment mean, in percent
G_{S100}	grassland (managed or unmanagaed grass pasture, or herbaceous rangeland), 100-m buffer distance, segment mean, in percent
H_{tree}	height of riparian trees
L_R	reach length, in meters
L_S	segment length, in meters
max.BVC	bank vegetative ground cover, reach maximum, in percent
$max.CA_o$	open canopy angle, reach maximum, degrees
$max.CC_b$	extent of bank canopy closure, reach maximum, percent
$max.CC_c$	extent of channel canopy closure, reach maximum, percent
$max.R_i$	estimated incident solar radiation, reach maximum, MJ m^{-2} d^{-1}
$max.R_p$	potential solar radiation, reach maximum, percent
$max.t_J$	latest day of sampling, day of the year
$max.T_{w30}$	water temperature, daily maximum, 30-day mean, degrees Celsius
$max.T_{w60}$	water temperature, daily maximum, 60-day mean, degrees Celsius
max.V	current velocity, reach maximum, centimeters per second
$max.W_{bf}$	bankfull width, reach maximum, in meters
$max.W_w$	wetted width, reach maximum, in meters
min.BVC	bank vegetative ground cover, reach minimum, in percent
$min.CA_o$	open canopy angle, reach minimum, degrees
$min.CC_b$	extent of bank canopy closure, reach minimum, percent
$min.CC_c$	extent of channel canopy closure, reach minimum, percent
$min.R_i$	estimated incident solar radiation, reach minimum, MJ m^{-2} d^{-1}
$min.R_p$	potential solar radiation, reach minimum, percent
$min.t_J$	earliest day of sampling, day of the year
$min.T_{w30}$	water temperature, daily minimum, 30-day mean, degrees Celsius
$min.T_{w60}$	water temperature, daily minimum, 60-day mean, degrees Celsius
min.V	current velocity, reach minimum, centimeters per second
$min.W_{bf}$	bankfull width, reach minimum, in meters
$min.W_w$	wetted width, reach minimum, in meters
n_s	number of sites
OP	orthophosphate, dissolved, mg/L

Abbreviations and Symbols—Continued

Symbol	Explanation
OW_b	open water bodies, total-basin extent, in percent
Pool.p	pools, relative areal extent, in percent of reach
ρ (or *rho*)	Spearman's rank correlation coefficient, which ranges from -1 to +1
R^2	coefficient of determination, or proportion of total variance explained by the statistical model
RAFD	ash-free dry mass (organic material), coarse-grained benthic habitat, g m^{-2}
RBV	biovolume, coarse-grained benthic habitat, mm^3 cm^{-2}
Rc_b	row crops, total-basin extent, in percent
RCD	cell density, coarse-grained benthic habitat, 10^6 cells cm^{-2}
Rc_{dnr}	row crops, drainage-network riparian buffer, in percent
RCHL	chlorophyll *a*, coarse-grained benthic habitat, mg m^{-2}
R_i	estimated incident solar radiation, reach mean, MJ m^{-2} d^{-1}
Riff.p	riffles, relative areal extent, in percent of reach
R_p	potential solar radiation, reach mean, as a percentage of above-canopy total
Run.p	runs, relative areal extent, in percent of reach
SCHL	chlorophyll *a*, sestonic habitat, mg/L
SS	suspended sediment, mg/L
S_w	gradient, reach mean, m/km
t_J	day of the year, sequential number
TN	total nitrogen, mg/L
TP	total phosphorus, mg/L
T_{w30}	water temperature, daily mean, 30-day mean, degrees Celsius
T_{w60}	water temperature, daily mean, 60-day mean, degrees Celsius
V	current velocity, reach mean, centimeters per second
W	Wilcoxon rank-sum test statistic
$W{:}D_{bf}$	width-to-depth ratio, bankfull, reach mean, dimensionless
$W{:}D_w$	width-to-depth ratio, wetted, reach mean, dimensionless
W_{bf}	bankfull width, reach mean, in meters
W_{R25}	wetland land cover, 25-m buffer distance, reach mean, in percent
W_{R50}	wetland land cover, 50-m buffer distance, reach mean, in percent
W_{Rllt}	wetland land cover, longitudinal linear riparian transect, reach mean, in percent
W_{S100}	wetland, 100-m buffer distance, segment mean, in percent
W_{S150}	wetland, 150-m buffer distance, segment mean, in percent
W_{S250}	wetland, 250-m buffer distance, segment mean, in percent
W_{S50}	wetland, 50-m buffer distance, segment mean, in percent
W_{Sllt}	wetland, longitudinal linear riparian transect, segment mean, in percent
Wv_{R25}	woodland land cover, 25-m buffer distance, reach mean, in percent

Abbreviations and Symbols—Continued

Symbol	Explanation
Wv_{R50}	woodland land cover, 50-m buffer distance, reach mean, in percent
Wv_RFg_{llt}	woodland gap frequency, longitudinal linear riparian transect, reach mean, per km
Wv_RL_{llt}	woodland patch length, longitudinal linear riparian transect, reach mean, in meters
Wv_{Rllt}	woodland land cover, longitudinal linear riparian transect, reach mean, in percent
Wv_{S100}	woodland, 100-m buffer distance, segment mean, in percent
Wv_{S150}	woodland, 150-m buffer distance, segment mean, in percent
Wv_{S250}	woodland, 250-m buffer distance, segment mean, in percent
Wv_{S50}	woodland, 50-m buffer distance, segment mean, in percent
Wv_SFg_{llt}	woodland gap frequency, longitudinal linear riparian transect, segment mean, per km
Wv_SL_{llt}	woodland patch length, longitudinal linear riparian transect, segment mean, in meters
Wv_{Sllt}	woodlands, longitudinal linear riparian transect, segment mean, in percent
W_w	wetted width, reach mean, in meters
Ww_b	woody wetland, total-basin extent, in percent
Ww_{dnr}	woody wetland, drainage-network riparian buffer, in percent
$WwWv_b$	forest plus woody wetland, total-basin extent, in percent
$WwWv_{dnr}$	forest plus woody wetland, drainage-network riparian buffer, in percent
$WwWv_{R25}$	combined wetland and woodland, 25-m buffer distance, reach mean, in percent
$WwWv_{R50}$	combined wetland and woodland, 50-m buffer distance, reach mean, in percent
$WwWv_{Sllt}$	combined wetland and woodland, longitudinal linear riparian transect, segment mean, in percent
$WwWv_{S100}$	combined wetland and woodland, 100-m buffer distance, segment mean, in percent
$WwWv_{S150}$	combined wetland and woodland, 150-m buffer distance, segment mean, in percent
$WwWv_{S250}$	combined wetland and woodland, 250-m buffer distance, segment mean, in percent
$WwWv_{S50}$	combined wetland and woodland, 50-m buffer distance, segment mean, in percent

Riparian and Associated Habitat Characteristics Related to Nutrient Concentrations and Biological Responses of Small Streams in Selected Agricultural Areas, United States, 2003–04

By Ronald B. Zelt and Mark D. Munn

Abstract

Physical factors, including both in-stream and riparian habitat characteristics that limit biomass or otherwise regulate aquatic biological condition, have been identified by previous studies. However, linking the ecological significance of nutrient enrichment to habitat or landscape factors that could allow for improved management of streams has proved to be a challenge in many regions, including agricultural landscapes, where many ecological stressors are strong and the variability among watersheds typically is large. Riparian and associated habitat characteristics were sampled once during 2003–04 for an intensive ecological and nutrients study of small perennial streams in five contrasting agricultural landscapes across the United States to determine how biological communities and ecosystem processes respond to varying levels of nutrient enrichment. Nutrient concentrations were determined in stream water at two different sampling times per site and biological samples were collected once per site near the time of habitat characterization. Data for 141 sampling sites were compiled, representing five study areas, located in parts of the Delmarva Peninsula (Delaware and Maryland), Georgia, Indiana, Ohio, Nebraska, and Washington. This report examines the available data for riparian and associated habitat characteristics to address questions related to study-unit contrasts, spatial scale-related differences, multivariate correlation structure, and bivariate relations between selected habitat characteristics and either stream nutrient conditions or biological responses.

Riparian and associated habitat characteristics were summarized and categorized into 22 groups of habitat variables, with 11 groups representing land-use and land-cover characteristics and 11 groups representing other riparian or in-stream habitat characteristics. Principal components analysis was used to identify a reduced set of habitat variables that describe most of the variability among the sampled sites. The habitat characteristics sampled within the five study units were compared statistically. Bivariate correlations between riparian habitat variables and either nutrient-chemistry or biological-response variables were examined for all sites combined, and for sites within each study area.

Nutrient concentrations were correlated with the extent of riparian cropland. For nitrogen species, these correlations were more frequently at the basin scale, whereas for phosphorus, they were about equally frequent at the segment and basin scales. Basin-level extents of riparian cropland and reach-level bank vegetative cover were correlated strongly with both total nitrogen and dissolved inorganic nitrogen (*DIN*) among multiple study areas, reflecting the importance of agricultural land-management and conservation practices for reducing nitrogen delivery from near-stream sources. When sites lacking segment-level wetlands were excluded, the negative correlation of riparian wetland extent with *DIN* among 49 sites was strong at the reach and segment levels. Riparian wetland vegetation thus may be removing dissolved nutrients from soil water and shallow groundwater passing through riparian zones. Other habitat variables that correlated strongly with nitrogen and phosphorus species included suspended sediment, light availability, and antecedent water temperature.

Chlorophyll concentrations in seston were positively correlated with phosphorus concentrations for all sites combined. Benthic chlorophyll was correlated strongly with nutrient concentrations in only the Delmarva study area and only in fine-grained habitats. Current velocity or hydraulic scour could explain correlation patterns for benthic chlorophyll among Georgia sites, whereas chlorophyll in seston was correlated with antecedent water temperature among Washington and Delmarva sites. The lack of any consistent correlation pattern between habitat characteristics and organic material density (ash-free dry mass) within study areas may indicate that the density of organic matter is not generally sensitive to nutrient enrichment in small agricultural streams. For all sites, and for the Nebraska, Delmarva, and Georgia subsets of sites, the reach-mean areal coverage of aquatic macrophytes and macroalgae was strongly related to channel shading.

Data reduction techniques were applied to select a subset of 29 variables, representing 20 categories of habitat characteristics, for multivariate analysis. Factor analysis was used to identify and interpret three leading modes of variation (principal factors) in two data subsets—one for the Georgia sites and one for all other sites combined. The factor analysis for Georgia sites indicated that riparian land use and land cover (LULC) (wetland extent in particular) and channel shading correspond to dominant modes of variability in the habitat data set. The variables that best characterize variation in riparian habitat for the other four study areas included mid-channel measures of canopy shading, riparian cropland extent in the 15-meter buffer and 150-meter buffer, and measures of the patchiness of woodland cover in the 15-meter buffer (patch length and gap frequency). LULC metrics calculated for riparian buffers, particularly at the segment scale, were more correlated with the principal modes of variation in the overall habitat data set than was LULC extent for the total basin drained by each site.

Correlations of woodland extent within 15 to 50 meters of the channel (reach- and segment-level data) with woodland extent in a series of longitudinal bands of the riparian buffer that were located at increasing distance from the channel showed decreased strength as the compared band shifted beyond the first 50 meters from the channel, becoming negligible for areas beyond 100 meters from the channel. For many of the studied agricultural streams, the riparian buffer includes a heterogeneous mix of riparian and upland land covers when the summarized buffer area extends more than about 50 to 100 meters from the streambank, depending upon basin (or stream) size. Comparisons between the extent of reach- and segment-level median values of woodland and other cover types within the riparian buffer extending 50 meters from the stream suggest that the reach length used for this study generally is not long enough to accurately represent both the overall composition and patch structure that characterizes the riparian areas along small, agricultural streams.

The mean extent of forest plus woody wetland ranged from 5.4 to 76 percent of the riparian buffer area. For the Georgia sites, where riparian woody wetlands were more extensive than for any other study area, canopy closure over the channel was greatest, whereas it was least for sites in Washington and Nebraska.

To the extent that riparian woodland is the most important LULC type affecting algal-nutrient relations, correlations indicated that basin characteristics might be effective surrogate predictors of riparian effects at the drainage-network scale. But the results also indicated that basin-level cropland was not an accurate surrogate for riparian cropland extent.

Introduction

Effective stream management depends on a comprehensive understanding of the complex interactions among riparian and stream habitat, water chemistry, and biological communities. The importance of nutrient enrichment as a stressor on aquatic communities has been widely recognized (Mosisch and others, 2001; Dodds and others, 2002; Mulholland and others, 2004; Alexander and Smith, 2006; Scott and others, 2007; Munn and others, in press). Relations between algal biomass and nutrient concentrations in stream environments typically have been weak (Dodds and others, 2002; Munn and others, in press) because of the interaction of physical and biological factors. These interactions include direct and indirect effects of riparian habitat on aquatic biota, such as the direct effects of riparian woodland shading or the indirect effects of retaining eroded upland sediment by riparian ground cover. Naiman and others (1993) defined the riparian corridor as the area that includes the stream channel and adjacent overbank terrestrial zone, where vegetation is affected by a shallow water table and (or) regime of frequent flooding. Channel banks clearly are key components of riparian corridors, and bank habitat and functions are to some degree inseparable from the function of the larger riparian system (Florsheim and others, 2008).

The factors governing biota-habitat relations include chemical and physical characteristics of the habitat. Riparian zone functions are related to stream chemistry through retention and cycling of nutrients and other contaminants (Florsheim and others, 2008). Some of the physical factors that also have commonly been identified as controlling algal biomass or biodiversity include light limitation from canopy shading (Mosisch and others, 2001; Kiffney and others, 2004) and turbidity (Munn and others, 1989), water temperature (Kilkus and others, 1975; Munn and others, 1989), and hydraulic disturbances (Powers, 1992; Biggs, 1995) including floods, fluvial erosion, and mass wasting of streambanks.

Present-day understanding of biota-habitat relations in streams is based primarily on comparative studies that described statistical relations between habitat variables and measures of aquatic community structure or function (Hawkins and others, 1993; Kiffney and others, 2004) or, more recently, between habitat-related stressors and ecological condition (Van Sickle and others, 2006; Munn and others, in press). Results from comparison studies may be confounded if the relative importance of various habitat factors varies with habitat type; thus, it may be important to study the effects of individual habitat features (for example, cover or stream shading) while holding other habitat factors as constant as possible (Hawkins and others, 1993).

Comparative study designs also commonly involve stratification by ecological or other geographic regions. Strong regional contrasts exist in distribution patterns of nutrient-enriched streams and in patterns of least-disturbed or non-enriched streams (Omernik, 1987; Dodds and others, 1998; Dodds and Oakes, 2008). For example, recent studies by Van Sickle and others (2006) used ecoregion-specific concentration ranges of total N and total P as indicators of ecological stress on stream biota. Similarly, Dodds and Oakes (2008) examined ecoregional differences in the relations between nutrient concentrations and riparian land cover. Nevertheless, linking the ecological significance of nutrient enrichment to habitat or landscape factors has proved to be a challenge in many regions where multiple ecological stressors exert strong effects and the natural variability among watersheds in nutrient-transport pathways typically is large.

Given the vast extent of agricultural areas in the United States and the great number of streams affected by agricultural practices, there is clearly a need to refine the understanding of stream habitat factors that affect or control nutrient enrichment and algal biomass. To address this need, the U.S. Geological Survey (USGS) National Water-Quality Assessment Program (NAWQA) began in 2001 a study of nutrient enrichment effects (the NEET study) on agricultural stream ecosystems. The primary objective of the study was to determine how biological communities and ecosystem processes respond to varying levels of nutrient enrichment in agricultural streams from contrasting environmental settings.

Study areas within five NAWQA study units (fig. 1) were selected to represent a cross section of agricultural landscapes across the conterminous United States. Given the levels of agricultural intensity within the study areas, the selected sampling sites represent primarily the nutrient-enriched end of the overall gradient of enrichment conditions, particularly for nitrogen (Munn and others, in press). Munn and Hamilton (2003) discuss in greater detail the five areas studied within the first group of NEET study units (fig. 1)—Central Columbia Plateau and Yakima River Basin, Central Nebraska, Delmarva Peninsula, Georgia Coastal Plain, and White, Great, and Little Miami River Basins (hereinafter called the White-Miami River Basins).

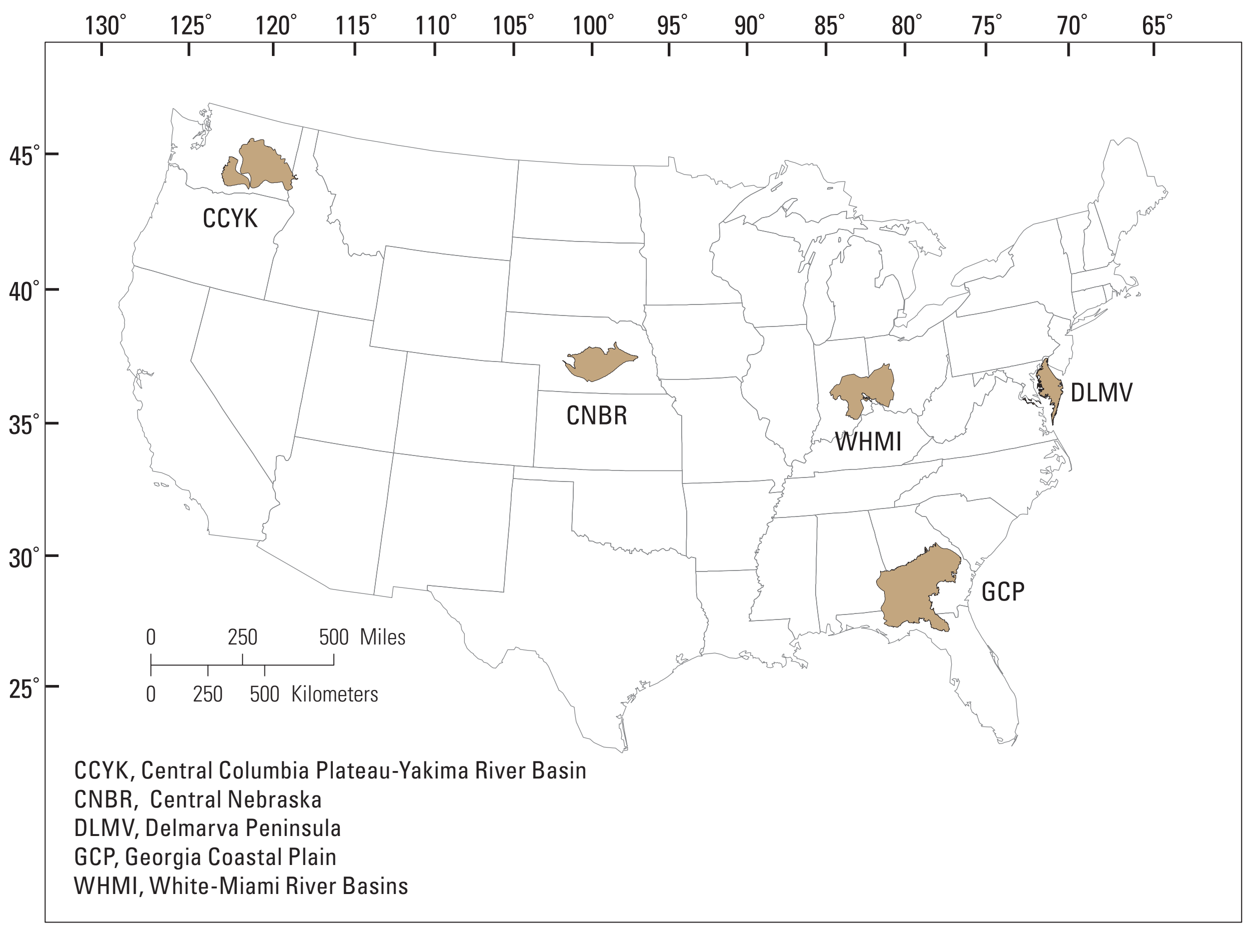

Figure 1. Location of study areas sampled within the initial group of study units included in the Nutrient Enrichment Effects topical study, 2003–04.

Purpose and Scope

This report addresses five primary questions through the examination of a variety of riparian habitat and associated characteristics in the five study areas:

(A) How do the study areas differ in regard to riparian habitat, including land use?

(B) How does spatial scale affect land-use and land-cover characteristics of riparian buffers?

(C) What subset of habitat characteristics captures most of the variability in riparian and associated habitat conditions, including land use?

(D) What riparian and associated habitat characteristics best explain stream nutrient concentrations?

(E) What riparian and associated habitat characteristics best explain biological responses?

Variables examined include field measurements of riparian habitat (at reach and transect scales), the extent or spatial structure of general land-use and land-cover types in riparian areas that were measured by using geographic information system (GIS) techniques and aerial photo interpretation (at reach, segment, and basin scales), and associated habitat features. Associated habitat characteristics include selected in-stream physical habitat indicators, including water temperature, velocity, and stream wetted width. Response variables include dissolved and total concentrations of nutrients (nitrogen and phosphorus) in streams, together with selected indicators of aquatic biological responses to riparian/chemical factors (chlorophyll *a*, organic material, periphyton biovolume, and extent of macrophyte or macroalgae cover).

Watershed sources and hillslope processes were largely beyond the scope of consideration for this report. The authors recognize, however, that an understanding of nutrient enrichment effects cannot be complete without accounting in greater detail than was possible herein for nutrient sources, short- and long-term storage, transport mechanics, and chemical transformations.

Physical and Biotic Processes and Process Controls

Hydrogeomorphic Regime.—Although restoration of degraded stream-riparian ecosystems may sometimes involve restoration of physical habitat features that have been damaged or lost through channel alteration (Hawkins and others, 1993), riparian systems, including their vegetative diversity, are fundamentally dependent upon the streamflow regime that periodically restructures the entire floodplain environment and produces strong spatial gradients in substrate, moisture, and temperature (Ward and others, 1999; Johnson, 2002; Florsheim and others, 2008). Flow regulation, either by dams or by extensive diversion systems, has disrupted the natural flow regime of many streams and thereby altered the processes that sustain channel and riparian ecosystems (Ward and Stanford, 1995; Johnson, 2002). One of the key processes for maintaining the characteristic diversity of riparian environments is lateral channel migration through cut-and-fill alluviation (Johnson, 2002; Florsheim and others, 2008). This process, strongly dependent upon high flows, is known to deliver a substantial fraction of the total sediment supply (Fitzpatrick and others, 1999) and much of the large woody debris load into alluvial streams. It also can maintain close proximity of the channel to woodland canopy along cutting banks, and provide for complete rejuvenation of the successional sequence of the riparian woodland on the depositional banks (Florsheim and others, 2008). Human modification of the natural processes of lateral migration (for example, by straightening channels or constructing bank revetments) and woody debris loading has had major effects on in-stream hydraulic habitat. Within the stream environment, the distribution of hydraulic conditions, both spatially and temporally, often governs the abundance and composition of plant communities, whereas, for unshaded streams, nutrient limitation is equally important (Biggs, 1996).

Spatial and Temporal Scale.—The relative importance of various environmental factors may depend strongly on the spatial scale of observation (Lanka and others, 1987; Crowl and Schnell, 1990). For example, the effect of bank vegetative-cover type on stream width was found to be dependent on stream size (Anderson and others, 2004). For small streams where the riparian canopy completely closes over the channel, understory growth is suppressed and banks lose the protection afforded elsewhere by dense root mats and herbaceous ground cover. Development of general models of stream biota-habitat relations has been hindered by lack of progress in integrating biotic responses at multiple spatial and temporal scales (Hawkins and others, 1993). Despite the lack of general understanding, management activities have been initiated on rivers at local scales in attempts to reverse declines in stream habitat and biodiversity (Galat and others, 1998); however, the effectiveness of small-scale projects lacking systemic improvements in the streamflow and sediment regimes is unknown (Johnson, 2002).

A conceptual model of habitat factors controlling plant growth in streams (Biggs, 1996) shows that disturbances regulate the major losses of aquatic plants. Moreover, the temporal scale of hydraulic disturbances and the spatial scale of variability in channel habitats are major components of the disturbance factor.

Riparian Land Cover.—At the interface between the aquatic and terrestrial environments, riparian corridors are some of the most productive and diverse of terrestrial ecosystems (Naiman and others, 1993). Although they typically represent a small proportion of the total drainage area, riparian corridors provide a disproportionately large number of ecological functions. In central Illinois headwater streams, riparian vegetation enhanced hydraulic-habitat diversity through woody debris inputs, and overhanging bank vegetation provided near-bank zones of slack water that provide cover and refugia for fish (Rhoads and others, 2003). Scott and others (2007) related percentages of riverine wetlands within the riparian zones of a watershed-scale stream network with yields of ammonia and nitrate, but not total organic nitrogen. They concluded that riparian areas high in woody wetlands suggest greater connectivity with the floodplain and river, and such areas have high biogeochemical transformation rates, including mineralization, nitrification, and denitrification.

Insolation and Shading.—By reflecting or absorbing insolation (incoming solar radiation), the riparian canopy alters the quantity and quality of light available for aquatic primary production (Gregory and others, 1991). Biotic communities responded to a gradient in the light regime that was related to differences in riparian buffer width (Kiffney and others, 2003, 2004). In a conceptual model of factors controlling plant growth in streams, Biggs (1996) noted that production is regulated primarily by light and nutrient availability. The structure and composition of the riparian plant community, and vegetation height in relation to channel size, largely control the degree of shading of streams (Gregory and others, 1991).

One of the key components of the River Continuum Concept (Vannote and others, 1980) is the importance of shading on the balance between in-stream production and respiration. In the River Continuum Concept, predictable patterns of net ecosystem metabolism and primary production theoretically extend from headwater streams to large rivers, and the transition between a net heterotrophic stream to an autotrophic stream is largely controlled by the amount of incoming solar radiation to the channel. In the arid to semi-arid western United States, however, the relatively "open" canopy conditions of even headwater streams can result in autotrophic stream ecosystems (Minshall, 1978).

The importance of light and inorganic nitrogen availability to primary production (Mosisch and others, 2001) and the control exerted on periphyton biomass by light and consumption by grazers (Minshall, 1978; Kiffney and others, 2004) have been demonstrated. Exposure to sunlight also will increase the photochemical oxidation of organic nitrogen during its downstream transport, resulting in greater production of organic matter that is available to drive respiration (Scott and others, 2007). Although the most bioavailable pool of organic nitrogen may be consumed quickly within small headwater streams (Brookshire and others, 2005), organic matter photolysis along the stream network continually produces small, labile organic nitrogen compounds that provide both nitrogen and carbon resources for the bottom of the aquatic food chain (Scott and others, 2007).

Channel Width.—Previous studies have found that by stratifying stream-width measurements according to bank vegetative or sedimentary characteristics, the downstream widening of channels in relation to increasing representative discharge could be modeled more reliably (Anderson and others, 2004). A downstream increase in channel width can limit the capacity of the riparian canopy to maintain complete closure over the stream, and thus partly regulates in-stream photosynthesis and growth of bank-understory plant communities. Thus, channel width may either affect or be affected by riparian habitat character.

On the basis of data from the intermountain western United States, Scott and others (2007) surmised that dissolved nutrients transported in streams with greater width and (or) shallower depth would have greater potential for mineralization because of greater contact with the stream bottom. They noted that both wider, shallower channels and periods of low flow and reduced velocity were associated with a greater contact area and (or) residence time of water in channel areas with higher microbial processing rates, such as the benthic and hyporheic zones. Lower than expected concentrations of nitrate in streambed pore water at two of the NEET study sites were attributed to removal by denitrification (Tesoriero and others, 2009).

Organic Materials.—Aquatic organisms can be autotrophic, relying on carbon dioxide as the primary source of carbon for their cells, or heterotrophic, acquiring carbon in its organic form, either from other organisms (dead or living) or from their aquatic chemical environment (Dodds, 2002). Although the important role of allochthonous material—organic matter that falls into a stream, such as leaf and litter input—as a source of energy for aquatic food webs is well established (Cushing and Allan, 2001), no data were collected for the NEET study that can directly indicate the abundance of those inputs. Canopy closure and other indicators of riparian vegetation are indirect indicators of seasonally variable loading from particulate organic matter. But as Minshall (1978) suggests, small streams wherein periphyton produce only a minor accumulation of autochthonous material—organic matter produced within a stream, usually through primary production—may nevertheless continuously export organic matter at high levels because they receive an abundant part of the total allochthonous inputs.

Previous work has documented the vital role of large woody debris (LWD) in a variety of stream types, including numerous studies in forested, high-gradient drainages (as examples, see Marston, 1982; Lisle, 1986; Montgomery and others, 1995; and Richmond and Fausch, 1995). Papers by Mutz (2000), Rhoads and others (2003), Daniels (2006), and Gurnell and others (2000) have described the effects of LWD on habitat formation, sediment storage, channel morphology and stability, and as major roughness elements. In a review of the role of LWD, Gurnell and others (1995) noted the importance of management of woodland riparian buffers to enhance a wide range of physical habitat properties, including

LWD loading, amount of insolation, water temperature, current velocity, and substrate conditions. For the NEET study, direct measurement of LWD was limited to its presence or absence as providing cover for stream biota. A total of 55 such observations were made for each stream reach.

Suspended Sediment, Turbidity, and Bank Instability.— Riparian vegetation has been shown to promote channel stability through the mechanisms of root strength, shielding of the riparian substrate by flexible stems or leaves and by increasing hydraulic resistance during overbank flows, and flow deflection by submerged, near-bank LWD (Keller and Swanson, 1979; Gregory and others, 1991). Unstable banks contribute large sediment loads directly into channels, and thus affect turbidity conditions, particularly where banks are composed chiefly of silt or finer particles. Where suspended sediment impairs water clarity and limits light availability, it is a primary control on instream productivity and nutrient uptake (Vannote and others, 1980).

Data and Methodology

Five study areas composed the initial set of agricultural areas studied as part of the NEET (fig. 1). Riparian characteristics were sampled in 2003 in the Central Columbia Plateau-Yakima River Basin (CCYK) of Washington and the Central Nebraska (CNBR) study areas. The Georgia Coastal Plain (GCP), Delmarva Peninsula (DLMV), and White-Miami River Basins (WHMI) study areas were sampled in 2004. All GCP sites were in Georgia, whereas DLMV sites included streams in Delaware and Maryland, and WHMI sites included both Indiana and Ohio localities. A total of 143 stream sites were sampled for the NEET study in 2003–04. However, only 141 sites are included in this report because only those sites had essentially complete sets of riparian and associated habitat characteristics data. Sites were selected on the basis of an initial stratification of the population of stream segments from the National Hydrography Dataset (NHD). The stratification was based largely on expected stream size and basin characteristics, including drainage area, land use and land cover, soils, ecoregions, and estimated nutrient loadings. Details of the site selection process were presented by Brightbill and Munn (2008).

The NAWQA NEET study collected physical habitat data at the basin, segment, reach, and transect levels (Fitzpatrick and others, 1998; Brightbill and Munn, 2008). Biological samples were collected at the reach scale, whereas water samples were collected at the channel-transect level. However, because the water samples were depth- and width-integrated samples of a well-mixed wetted cross section (U.S. Geological Survey, variously dated), those samples are presumably representative for reach and segment levels as well. All data used for this study have been published by the USGS (table 1), though many data sets are disseminated only through the Web (http://pubs.usgs.gov/ds/345/).

In the following paragraphs, data sets and variables are identified, referenced, and discussed. The material is organized by the hierarchical levels of spatial scale. Quality assurance methods were used for selected data types, and are presented or referenced in the respective subsection corresponding to the data type.

Basin-Level Habitat Data

Existing geospatial data for drainage area boundaries were available for each sampling site (Nakagaki, 2006a). Drainage-area and other basin characteristics data were downloaded from the USGS NAWQA Data Warehouse (Bell and Williamson, 2006). For all study areas, basin-scale terrestrial habitat had been characterized using GIS to summarize land cover and a few other characteristics (Nakagaki, 2006a). Thematic data were summarized for two types of spatial areas—the entire basin draining to each water-chemistry sampling point (total basin), and the buffer zone extending a short distance in both directions away from the stream for the drainage network upstream from each water-chemistry sampling point (drainage-network riparian buffer). The buffer distance ranged from 75 to 105 meters (m), typically as a function of the spatial resolution and orientation of raster cells used to represent the national GIS data for the drainage networks, but was nominally 90 m on each side of the stream (Falcone, 2006).

The percentage of each land-use and land-cover type within the total basin drained by each stream-sampling site was determined for all sites. The source data were an enhanced version of the 30-m resolution, circa-1992 National Land Cover Dataset, that is, the “NLCDe-92” data base (Nakagaki, 2006b). Each land-cover type was identified by a two-digit code in the NLCDe-92 data base. Additionally, the distribution of land-cover types along riparian buffers of the drainage network upstream from each stream-sampling site was determined for all sites using NLCDe-92 (Falcone, 2006).

For both the total basin and riparian buffers of the drainage network, an additional variable was calculated that represented the sum of the areal extent of selected land-cover types. “Cropland and pasture” was the sum of four NLCDe-92 land-cover types (codes 81-84): pasture/hay (81), row crops (82), small grains (83), and fallow (84). “Grassland” was simply the NLCDe-92 land-cover type encoded as type 71.

Table 1. Summary of data sources used in this study.

[USGS, U.S. Geological Survey; NDW, NAWQA Data Warehouse; NHD, National Hydrography Dataset; NLCDe-92, National Land Cover Dataset, enhanced version; DOQ, digital orthophoto quadrangles; m, meters; HDAS, Habitat Data Analysis System; –, not applicable; Study areas: CCYK, Central Columbia Plateau-Yakima River Basin; CNBR, Central Nebraska; DLMV, Delmarva Peninsula; GCP, Georgia Coastal Plain; WHMI, White-Miami River Basins]

Data set	Source	Map scale	Spatial resolution	Time period	Data publisher	Reference
Basin-Level Riparian Habitat						
Drainage area	USGS NDW	1:24,000	–	–	USGS	Bell and Williamson, 2006
Drainage network	NHD	1:100,000	–	–	USGS	U.S. Geological Survey, 2000
Land cover	USGS NLCDe-92	–	30 m	1988–93	USGS	Nakagaki, 2006b
Land cover along riparian buffer	USGS NLCDe-92	–	30 m	1988–93	USGS	Falcone, 2006
Segment-Level Riparian Habitat						
Stream segment	Delineated from DOQ	1:12,000	2 m	[1]1990–2000	USGS	Johnson and others, 2007
Land use and land cover	Classified from DOQ	1:12,000	2 m	[1]1990–2000	USGS	Johnson and others, 2007
Reach-Level Riparian Habitat						
Stream reach	Delineated from DOQ	1:12,000	2 m	[1]1990–2000	USGS	Johnson and others, 2007
Physical habitat	USGS NDW	–	Various	July 2003 – Oct. 2004	USGS	Bell and Williamson, 2006
Physical habitat	USGS HDAS	–	Various	July 2003 – Oct. 2004	USGS	Brightbill and Munn, 2008
Land use and land cover	Classified from DOQ	1:12,000	2 m	[1]1990–2000	USGS	Johnson and others, 2007
Reach-Level Water Quality						
Nutrient concentration	USGS NDW	–	Integrated channel section	June 2003 – Sept. 2004	USGS	Bell and Williamson, 2006
Chlorophyll concentration, sestonic	USGS NDW	–	Integrated channel section	July 2003 – Aug. 2004	USGS	Bell and Williamson, 2006
Chlorophyll concentration, benthic	USGS NDW	–	Targeted habitat points	July 2003 – Aug. 2004	USGS	Bell and Williamson, 2006

[1]DOQ imagery acquisition dates were from 1990–91, 1995–96, 1998, and 2000 for CCYK sites; 1993 for CNBR sites; 1995–98 for DLMV sites; 1999 for GCP sites; and 1990, 1994–95, and 1998–99 for WHMI sites.

Segment-Level Habitat Data

The sampled segment was defined as the main stem upstream from the water-sampling site for a length equal to the base-10 logarithm of the upstream drainage area (Johnson and Zelt, 2005). Segment sampling length (L_s) ranged from 278 to 3,742 m. The interquartile range (central half of the frequency distribution) of segment lengths extended from 1,947 to 2,425 m, and average L_s by study area ranged from 1,910 to 2,542 m.

The riparian area was characterized on the basis of multiple fixed-width buffer zones along the stream segment. At the segment scale, four specific buffer zones were delimited on the basis of respective buffer distances from the stream centerline—50, 100, 150, and 250 m. The relative extent of various categories of land use and land cover (LULC) within each buffer zone had been estimated by delimiting and classifying polygons of contrasting LULC on digital orthophoto quadrangles (DOQ) using standard methods for aerial photo interpretation (Johnson and others, 2007).

Additionally, riparian LULC had been summarized for each segment by using a longitudinal riparian transect that was located on each bank, again using the methods of Johnson and Zelt (2005). The two riparian transects were located using a 15-m offset distance shoreward from the streambank location, which had been estimated on the basis of the stream centerline and one-half the reach-average bankfull width.

Riparian LULC data were downloaded from the USGS NAWQA Data Warehouse (Bell and Williamson, 2006). The LULC data set included the suite of LULC variables (Johnson and Zelt, 2005) for all sites. As a quality-assurance step, the authors used the nonparametric Wilcoxon signed ranks test (Helsel and Hirsch, 2002) to determine if sampled reaches were representative of the segments in which they were located, particularly with respect to the areal extent of riparian woody vegetation. This comparison was made by testing for differences within the riparian areas bounded by the 50-m buffer along stream centerlines.

In addition to the extent of woodland in the riparian area, USGS investigators also compiled data for the frequency and size of openings through the woody vegetation that help describe the woodland patch structure (Brightbill and Munn, 2008). The number and sizes of woodland and non-woodland LULC polygons intersected by the riparian longitudinal transects were compiled using GIS overlay analysis of the DOQ-based LULC classification with the transect lines (Johnson and Zelt, 2005; Johnson and others, 2007).

Reach-Level Habitat Data

The sampling reach was defined as a length of stream equal to 20 times the bankfull width (Fitzpatrick and others, 1998). Sampling-reach length ranged from 90 to 560 m. Reach-scale data for riparian and stream physical habitats were downloaded from the USGS Biological Transactional Database (BioTDB) for NAWQA ecological data. These data sets are published either in Brightbill and Munn (2008) or in the NAWQA Data Warehouse (Bell and Williamson, 2006). Other than land use and land cover, most of the habitat characteristics analyzed were calculated from the field-measured parameters using a software extension of the BioTDB, known as the NAWQA Habitat Data Analysis System (HDAS) (U.S. Geological Survey, written commun., 2006, accessed at http://nc.water.usgs.gov/usgs/biotdb/documentation/hdas.html).

Riparian Land Use and Land Cover

The riparian area also had been characterized using fixed-width buffer zones along the stream reach. At the reach scale, data were available for two riparian buffer-zone widths—25- and 50-m buffers from the stream centerline (Johnson and Zelt, 2005). The relative extent of various categories of land use and land cover within each buffer zone was estimated using methods identical to those for the segment-level characteristics.

Additionally for the longitudinal transect, the LULC for each reach was determined using the corresponding part of the segment-level data. Data for the frequency and size of openings through the woody vegetation adjacent to the sampling reaches were compiled using methods identical to those for the corresponding segment-level characteristics.

Canopy Shading and Light Availability

Transect measurements of open-canopy angle above the channel centerline and canopy closure above bank and mid-channel locations were collected at each stream reach (Fitzpatrick and others, 1998). Reach-level mean, minimum, and maximum values were calculated for these characteristics using HDAS.

Solar radiation was estimated with data from a Solar Pathfinder™ (www.solarpathfinder.com) used at mid-channel on multiple transects per sampling reach (Brightbill and Munn, 2008). The onsite observations of overhead conditions, that is, shade-providing objects and open sky, were recorded for all zenith angles and compass directions from the sampling point (Platts and others, 1987). This allowed subsequent calculation of the average potential solar radiation (R_p, in percent) that could be incident at each point for any month of the year. The number of transects where overhead conditions were recorded ranged from three to six per site. The mean value of R_p at each site also was multiplied by the measured monthly average incident solar radiation at the nearest monitoring station to estimate the incident radiation (R_i) for each site. The incident and potential radiation data are available in Brightbill and Munn (2008).

For example, available data for monthly average incident solar radiation at Grand Island, Nebr., for 1961–90 were published by National Renewable Energy Laboratory (1995) and were used with Solar Pathfinder™ observations for 27 of the CNBR sampling sites. Because the monthly averages used were not those from the year of sampling, the incident radiation values clearly are only estimates. Reach-level values of R_i and R_p also were very strongly rank correlated (Spearman's *rho* = 0.989) because of the lack of records for incident solar radiation within any of the study areas. Only one or two weather stations per study area were used to calculate R_i. Therefore, the values of R_i were rescaled values of R_p that used only one or two rescaling factors per study area.

Water Quality

Although the authors recognize that nutrient concentrations in streams typically are related to streamflow and other seasonal factors, and sediment-associated constituents often follow a specific pattern (hysteresis) during individual high-flow events (Robertson, 2003), our study was focused on summer stable-flow periods to facilitate sampling efficiency. Each site was visited twice to collect water samples for nutrient analysis. Samples were collected approximately one month prior to the biological sampling, and then again during the biological sampling. This was done to bracket the period just prior to biological sampling, which is a critical period for algal growth. Water temperature, discharge, turbidity, and pH were measured, and concentrations of dissolved oxygen and suspended sediment also were determined. Methods used for equipment decontamination, sample collection, filtering, onsite measurements, and other processing are described in the USGS National Field Manual (U.S. Geological Survey, variously dated). Water chemistry data for samples collected for the five study areas were downloaded from the USGS NAWQA Data Warehouse (Bell and Williamson, 2006).

Aquatic Biological Measures

Biological data used in this report include algal biomass (as milligrams per liter [mg/L] of chlorophyll *a*), organic material (as ash-free dry mass), algal biovolume, and aquatic macrophytes plus macroalgae cover. Data for the aquatic biological response variables were published by Brightbill and Munn (2008).

Algal biomass was estimated using data for chlorophyll *a* collected during the growing season (July to August). Four types of algal samples (habitats) were collected for determination of chlorophyll *a*: (1) suspended (sestonic); (2) epipelic (fine-grained benthic); (3) epilithic (coarse gravel); and (4) epidendric (woody debris); but not all types were collected at each site. Hereinafter, the chlorophyll concentration determined for the latter two sample types or habitats (rock or wood) is symbolized as *RCHL*, and the habitats collectively referred to as coarse-grained benthic habitat.

Sestonic (suspended) algae were sampled from an aliquot of the water sample by using a churn splitter. The water sample was filtered through a 47-millimeter (mm)-diameter glass fiber filter with 0.3-micrometer (μm) pore size. The filter was folded into quarters, wrapped in aluminum foil, placed in a labeled Petri dish, placed in a plastic bag, and frozen on dry ice for shipment to USGS National Water Quality Laboratory (NWQL) (Moulton and others, 2002). Both chlorophyll *a* and pheophytin *a* were analyzed by NWQL using protocols outlined in Arar and Collins (1997).

Benthic algae within coarse-grained habitat areas were sampled using methods described in Moulton and others (2002). A subsample of the coarse-grained benthic sample was filtered for chlorophyll *a* (Moulton and others, 2002), frozen on dry ice, and sent to NWQL for analysis (Britton and Greeson, 1987); the remainder of the sample was retained and preserved (Moulton and others, 2002) and sent to the Academy of Natural Sciences of Philadelphia for identification and enumeration processing (Charles and others, 2002).

Benthic algae also were sampled in the depositional habitat (DTH) areas of organically rich or sandy sediment along stream margins, using methods described in Moulton and others (2002). Because NAWQA does not have a standardized method for the field processing of DTH chlorophyll, methods were modified from Stevenson and Stoermer (1981). In order to filter the DTH chlorophyll sample and not clog the filters with sand, an elutriation process was used to separate the algae from the fine-grained material. After adding 100 milliliters (mL) of drinking water, the sample was agitated and then allowed to settle for 5 seconds. The algal-water mixture was poured into a clean 1-liter (L) plastic container, taking care not to introduce sand into the clean container. This process was repeated two more times for a total of three elutriations. The elutriated sample was homogenized by shaking the algal-water mixture in the 1-L container, and then a 10-mL subsample was withdrawn from the mixture and filtered as described in Moulton and others (2002). If relatively few solids were present on the filter surface, the filtering process was repeated until a thin, pigmented film was deposited on the filter. The filter was then removed and processed as described in Moulton and others (2002), frozen on dry ice, and sent to NWQL for analysis (Britton and Greeson, 1987). The remaining DTH sample was preserved according to Moulton and others (2002) and sent to the Academy of Natural Sciences of Philadelphia for identification and enumeration processing (Charles and others, 2002).

The method used for determining the percentage of either submerged macrophytes or macroalgae cover, or both, was modified from that described by Biggs and Kilroy (2000). Five equally spaced points along each of the 11 transects were sampled (Brightbill and Munn, 2008). A 0.09-square-meter (m^2) quadrat (a marked 30×30-centimeter [cm] rectangle used to isolate a sample area for the purpose of counting the population of different species in that area) was placed at each sampling point. The cover of filamentous algae and/or submerged macrophytes greater than 3 cm in length was estimated to the nearest 10 percent. These 55 values were then averaged to obtain an estimate of the average percentage of cover of the site by macroalgae and macrophytes.

Data Analysis

A variety of statistical analyses was applied to the data used in this study, and those analyses and their results are described in the following subsections. The S-Plus software system (Insightful Corp., 2005; TIBCO Software, 2008) was used for all statistical analyses. Laboratory results for some determinations of organic material (as ash-free dry mass) were reported as left-censored values (that is, as less than the laboratory reporting level [LRL]). There were no more than three left-censored values per sampled habitat type, and no more than 8 percent of any study area's sites had left-censored values for organic material. For data analysis, these censored values were replaced with one-half the method detection limit, or one-quarter of the LRL (Childress and others, 1999).

For determinations of dissolved nutrient concentrations at some sites, results for one or both sampling periods were reported as left-censored values (Brightbill and Munn, 2008). The statistical analyses used in this report required that each sampled site have an associated concentration for each nitrogen and phosphorus species. Therefore, concentrations of nutrient species reported as left-censored values were assigned a concentration of one-half the method detection limit, or one-quarter the LRL (Childress and others, 1999). Because there are concerns about potential bias in the statistical distribution of data when using this substitution approach, we compared the data set derived using the value-substitution approach (one-half detection limit method) with an alternative data set derived using a method that relies on using the inferred distribution to estimate the mean and variance (Helsel, 2005). In this study, we compared these two methods for three nutrient species: dissolved ammonia (36–53 percent non-detections), dissolved nitrite plus nitrate (8 percent non-detections), and dissolved orthophosphate (14–19 percent non-detections). Ranges of non-detection percentages reflect two sampling periods. Results from the two-group maximum likelihood estimation test (Helsel, 2005) indicated that for all three comparisons there was no significant difference between the two methods employed to handle left-censored values. Therefore, the use of a value-substitution approach was deemed appropriate for this study.

Univariate Summaries

Statistical summaries of individual habitat or response variables used measures of central tendency and dispersion about the center. Measures of central tendency included the mean or the median (50th percentile). Dispersion was summarized using either selected percentiles or the coefficient of variation (CV), which is the standard deviation divided by the mean, and was reported as a percentage of the mean in this report by simply multiplying the ratio by 100.

A total of 141 sites were sampled and had HDAS-calculated values available. In some cases, univariate summaries are reported for all 141 sites, but generally are reported by study area. The distribution of the 141 sites among the study areas is listed in table 2, ranging from 25 to 30 sites per study area.

Table 2. Summary of number of sampling sites by study area.

[CCYK, Central Columbia Plateau-Yakima River Basin; CNBR, Central Nebraska; DLMV, Delmarva Peninsula; GCP, Georgia Coastal Plain; WHMI, White-Miami River Basins; PCA, principal components analysis; LULC, land use and land cover; DOQs, digital orthophoto quadrangles (interpreted)]

Measurement or analysis group	Total	Study area code				
		CCYK	CNBR	DLMV	GCP	WHMI
Number of sites	141	29	28	25	29	30
Number of sites not included in PCA or factor analyses	5	0	0	0	3	2
Number of sites with:						
Basin-level riparian LULC data	140	28	28	25	29	30
Segment-level LULC data from DOQs	141	29	28	25	29	30
Reach-level LULC data from DOQs	141	29	28	25	29	30
Reach-level on-site physical habitat data	141	29	28	25	29	30
Reach-level insolation estimates	136	28	28	23	29	28
Chlorophyll data for fine-grained benthic habitat	136	29	26	24	29	28
Reach-level sestonic chlorophyll data	136	29	28	23	28	28
Organic material data for coarse-grained benthic habitat	140	29	27	25	29	30
Organic material data for fine-grained benthic habitat	137	29	26	25	29	28
Reach-level macrophyte plus macroalgae	140	29	28	25	29	28
Water-quality data for nutrients	141	29	28	25	29	30
Water-quality data for sediment	139	29	28	24	28	30

Comparison Tests

Two types of statistical comparisons were made: tests for significant differences between groups, and evaluations of the strength of rank correlations. Declaration of significance for differences between groups was based on the computed probability (*p*-value) of obtaining the specific test result (test statistic) when the null hypothesis of no real difference between groups (in either direction) is true. Such a hypothesis corresponds to a “two-tailed” test in which no group is presumed beforehand to have larger values of the tested variable. Significant differences between groups were declared at the 95-percent confidence level ($\alpha = 0.05$), that is, when the *p*-value was less than 0.05.

For comparing two groups of sample data, in most cases the data sets were independent and the Wilcoxon rank-sum test (Wilcoxon, 1945) was used (Helsel and Hirsch, 2002). For large data sets, or if there are tied ranks, an exact *p*-value cannot be computed for the rank-sum test. Instead, the normal approximation given by Lehmann (1975, p. 20) was used. In instances where the data were for paired cases, the Wilcoxon signed-rank test was used (Helsel and Hirsch, 2002). For large datasets (more than 25 pairs), or if there are tied ranks, an exact *p*-value cannot be computed for the signed-rank test, and the normal approximation given by Lehmann (1975, p. 130) was used.

For comparing three or more groups of sample data, the Kruskal-Wallis rank-sum test was used (Helsel and Hirsch, 2002). A large-sample approximation of the *p*-value of the rank-sum test statistic was reported (Insightful Corp., 2005).

Evaluations of correlation strength used Spearman’s rank correlation coefficient, *rho* (ρ) (Helsel and Hirsch, 2002), which was compared with a threshold value of 0.5. For a rank correlation test of 25 observational units, a test result of *rho* equal to 0.5 would correspond to a probability (*p*-value) of 0.0109 for a two-sided test of the null hypothesis that *rho* is zero. Values of *rho* greater than 0.5 are referred to as strong correlations, whereas values less than 0.5 are not discussed as providing independent evidence for a bivariate correlation. In some cases, however, the patterns of *rho* were discussed or graphed for a series of related variables, such as for a multi-scale series of related measures.

Multivariate Analyses

To gain insight into the correlation structure of the multivariate dataset, principal components analysis (PCA) was applied. The method of principal components (Hotelling, 1933) aims to reduce the dimensionality of a data set composed of multiple correlated variables. PCA accomplishes this by transforming the original variables to a new set of mutually uncorrelated variables, the principal components (PCs), which are ordered so that the first few PCs retain most of the total variance present in the data set (Joliffe, 2002). Consequently, the standardized linear coefficients estimated by PCA maximize the sum of the squared correlations of the first few PCs with the original variables (Dunteman, 1989). Following the PCA, the axes of the PCs were rotated using factor analysis to improve interpretability of the derived PCs, which by convention are called principal factors, or just factors, after they are rotated.

For this report, the objective of the multivariate analyses was to identify a minimum number of new variables that retained most of the information present in the riparian data set without including uninterpretable or trivial variation. Because there were more variables than sampling sites in the data set, a preliminary part of the multivariate analysis involved data reduction (using rank-correlation analysis; see section, “Variable Selection”) until the number of retained variables was less than about one-fourth the total number of sites. Various rules of thumb are used to determine the size of the sample of objects (sites in this case), but typically there are considerably more objects than variables to reduce the likelihood of identification of relations between variables that are actually the result of chance alone (Kachigan, 1986).

Exploratory data analyses for data reduction focused on two divisions of habitat variables, corresponding to: (1) LULC characteristics for various streamside buffer areas or sampling transects along the streams; and (2) reach-level habitat characteristics (that is, outputs from the HDAS). The riparian habitat and associated characteristics were grouped further into 22 categories of variables (table 3). Extreme redundancy among the variables within each habitat characteristics category was examined using rank-correlation methods.

After removing the most redundant variable(s) from each group of characteristics, the remaining variables were analyzed, first by using PCA, computed from the correlation matrix (rather than the covariance matrix) to equalize the weight of each variable. Following PCA, a factor analysis was conducted using the standardized scaling (*z*-scores) of the same data to gain additional understanding of the underlying interrelations among the selected set of variables. A *z*-score (z_x) is defined as

$$z_x = \frac{\left[x - \bar{x}\right]}{\sigma_x}, \qquad (1)$$

where

x is the nontransformed variable;
$\bar{x}$ is its mean value; and
σ_x is its standard deviation.

Once the principal factors and associated variable loadings had been examined and compared with the PCA results, an interpretive label was given to each principal factor. Strong correlations between principal factor scores and habitat variables not included in the PCA or factor analysis also aided or confirmed the interpretation of principal factors by suggesting a larger suite of associated variables. Details of the multivariate analysis approach follow, including considerations related to both variable selection and site retention.

Table 3. Habitat characteristics groups from which analysis variables were selected.

[Groups 1–11 were measured using geospatial data, whereas groups 12–22 were measured onsite. m, meters; PCA, principal components analysis]

Group No.	Habitat characteristics group	Scale level	Theme	Number of variables selected for PCA
1	Cropland and pasture extent within entire basin	Basin	Land use and land cover	1
2	Woody wetland extent within entire basin			1
3	Forest extent within entire basin			1
4	Cropland extent within 100 to 250 m of streams	Segment		1
5	Wetland extent within 100 to 250 m of streams			[1]0
6	Woodland extent within 100 to 250 m of streams			1
7	Cropland extent within 50 m of streams	Segment and reach		2
8	Wetland extent within 50 m of streams			[1]0
9	Woodland extent within 50 m of streams			2
10	Woodland patch length	Segment and reach		1
11	Woodland gap frequency			2
12	Woody debris cover extent	Reach	In-stream cover	1
13	Overhanging vegetation cover extent			1
14	Geomorphic channel types		Hydrogeomorphic character	2
15	Hydraulic gradient and velocity			3
16	Bankfull channel width			1
17	Wetted stream width			2
18	Width-to-depth ratio			1
19	Bank vegetative ground cover or undercut bank		Other riparian habitat	2
20	Bank canopy closure			1
21	Channel canopy closure			2
22	Open canopy angle			1

[1]Variables initially selected from groups 5 and 8 were later excluded from the PCA because of their extremely non-normal frequency distributions.

Variable Selection

The habitat variables were grouped as described in the previous section. The Solar Pathfinder-derived variables were excluded from the PCA and factor analyses, and reserved for use in validation of the loading-based interpretation of principal components and factors. Water temperature and suspended-sediment concentration were not included in the PCA because each is affected by several of the other indicators and so may be considered physical responses to watershed and riparian characteristics. Because one of the objectives of the report was examination of the effects of scale on indicators of riparian habitat, variables were included that represented the entire drainage area as a point of reference for comparison with the segment- and reach-scale measurements of riparian indicators.

Indicators of shading and light availability included canopy measures, understory measures (bank vegetation cover density), in-stream measures (LWD), and measures related to shading geometry (channel width). Canopy measures included both channel- and bank-canopy closure; open-canopy angle above the channel; potential solar radiation, R_p; and incident solar radiation, R_i. Fewer sites had data for the Solar Pathfinder measures than for the other variables, so the measures R_p and R_i were excluded from the multivariate analyses. Correlations among the remaining canopy variables were examined using Spearman's rank-correlation coefficient, *rho*. For example, when all three summary variables for a canopy measure—that is, the minimum, mean, and maximum values for each reach—were strongly correlated, then the mean values were retained for the PCA. Moreover, when the minimum and maximum variables were not correlated strongly, but both were correlated with the reach-mean values, then both extrema were retained and the mean values were excluded.

One additional consideration influencing variable selection was the number of sites that may have lacked information for certain considered variables. To maximize the power of the multivariate analyses, variables sometimes were selected to retain as many sites as possible in the set having a complete suite of non-missing values for all retained variables. In one case, variable selection included a no-variance consideration. In both the GCP and WHMI study areas, all sites had full bank-canopy closure at one or more sampling transects. Therefore, the values of reach-maximum bank-canopy closure were always 100 percent, and that variable ($max.CC_b$) was not retained for multivariate analyses because, with no variance for so many sites, it was very non-normally distributed and contributed less information than reach-mean bank-canopy closure.

For the PCA of the combined data set, 20 of the 22 groups of habitat characteristics ultimately were represented in the set of included variables, including LULC characteristics (groups 1–4, 6, 7, and 9–11) for basin, segment, and reach levels of the habitat hierarchy, in-stream cover, hydrogeomorphic characteristics (groups 14–18), and other riparian characteristics measured onsite (groups 19–22) (table 3). Correlations among the variables in each group had been examined to identify and remove redundant (highly correlated) variables, as will next be described. The full definitions of the habitat (and other) variables referenced in the following descriptive paragraphs are given in the section,"Abbreviations and Symbols" at the front of the report.

Basin-level characteristics (groups 1 through 3) consisted of two variables each—one measure for the entire drainage area and the other measure representing only the riparian buffer zone (nominal 90-m buffer distance) along the entire drainage network. To retain the full range of spatial scales at which LULC data were collected, the variable retained from each of these three groups was the one representing the entire drainage area. Moreover, among the agricultural watersheds included in the study, the drainage-network riparian-buffer extent of land cover was strongly correlated with the total-basin extent for each of the LULC types included in the multivariate analyses—cropland and pasture ($rho = 0.893$), woody wetland ($rho = 0.963$), and forest ($rho = 0.963$).

Groups 4 through 11 include segment- and reach-level riparian LULC characteristics, and correlations within each of groups 4 through 10 were strong ($rho \geq 0.68$). In group 4, three cropland-extent variables correspond to the 100-, 150-, and 250-m width riparian buffers along the stream segment (C_{S100}, C_{S150}, and C_{S250}); in group 5, three wetland-extent variables correspond to those same buffer widths at the segment level (W_{S100}, W_{S150}, and W_{S250}); three woodland variables composed group 6 and correspond to those same segment buffer widths (Wv_{S100}, Wv_{S150}, and Wv_{S250}). The measure based on 150-m buffer width was selected from each of groups 4–6 (C_{S150}, W_{S150}, and Wv_{S150}). Group 7 comprised five cropland-extent variables corresponding to reach-level riparian buffer widths of 25 and 50 m (C_{R25} and C_{R50}), the segment-level 50-m buffer (C_{S50}), and the longitudinal-transect sample of reach- and segment-level cropland extent (C_{Rllt} and C_{Sllt}). The two group-7 variables with the weakest rank correlation (C_{R25} and C_{Sllt}) were selected for the PCA. Group 8 included five wetland-extent variables for buffer areas or transects that are direct counterparts to those of the cropland variables in group 7 (W_{R25}, W_{R50}, W_{S50}, W_{Rllt}, and W_{Sllt}). Based on the correlations within the group, three of these variables (W_{S50}, W_{Rllt}, and W_{R50}) were retained initially. Of five corresponding woodland-extent variables in group 9 (Wv_{R25}, Wv_{R50}, Wv_{S50}, Wv_{Rllt}, and Wv_{Sllt}), two (Wv_{R25} and Wv_{Sllt}) were retained for the PCA. Two woodland patch-length variables composed group 10 ($Wv_R L_{llt}$ and $Wv_S L_{llt}$ for the reach- and segment-level longitudinal-transect samples, respectively), and the segment-scale variable was retained for the PCA. Both of the woodland gap-frequency variables in group 11 ($Wv_R Fg_{llt}$ and $Wv_S Fg_{llt}$, for the reach- and segment-level longitudinal-transect samples, respectively) were retained for the PCA.

Groups 12–13 correspond to in-stream cover types that are associated with riparian habitat, and each group consisted of a single variable. In group 12, extent of cover from woody debris (*CvrWd*) was included because of its usual source in riparian woodland and its importance to periphyton (and macroinvertebrates) as a colonization substrate. Group 13 had a single variable, in-stream cover from overhanging vegetation (*CvrOv*), an ecological service provided by riparian vegetation.

The variables in groups 14–18 indicate hydrogeomorphic characteristics of the stream channel. Group 14 contained three geomorphic channel-unit extent variables whose values sum to unity for each site—the relative areal extent of pools, riffles, and runs (*Pool.p*, *Riff.p*, and *Run.p*, respectively). At least one variable was necessarily excluded to avoid an overspecification error, and because the extent of pools and riffles was not strongly correlated ($rho = 0.308$), both *Pool.p* and *Riff.p* were retained for the PCA. Six hydraulic variables were included in group 15; water-surface slope (S_w), reach-minimum, -mean, and -maximum current velocity (*min.V*, *V*, and *max.V*, respectively), coefficient of variation of current velocity (*cv.V*), and the Froude number that is the ratio of inertial and gravitational forces (*Froude*). Water-surface slope, reach-minimum velocity (*min.V*), and *Froude* were retained for the PCA.

Groups 16–22 each included a set of three variables (reach-minimum, -mean, and -maximum). Group 16 was thought to importantly affect stream shading through the geometric relation of channel width to tree height:

$$\tan(90 - \frac{CA_O}{2}) \cong \frac{2 \times H_{tree}}{W_{bf}}, \qquad (2)$$

where

CA_O is open canopy angle, in degrees;
H_{tree} is height of riparian trees; and
W_{bf} is bankfull channel width (group 16), measured in same units as tree height.

Reach-mean channel width was retained for the PCA data set because it was very strongly correlated with both reach extrema of channel width. Groups 17–18 were expected to represent the area over which nutrients can exchange between streambed and water column. Group 17 contained the reach-minimum, -mean, and -maximum wetted width ($min.W_w$, W_w, and $max.W_w$, respectively), and the coefficient of variation of wetted width ($cv.W_w$). Whereas the extrema were strongly correlated with mean wetted width, $cv.W_w$ was not correlated with W_w ($rho = 0.038$), so both were retained for the PCA data set. Group 18 included the reach-minimum, -mean, and -maximum ratio of wetted width to depth ($min.W{:}D_w$, $W{:}D_w$, and $max.W{:}D_w$, respectively). $W{:}D_w$ was retained because correlations within group 18 were strong ($rho \geq 0.66$).

The variables in groups 19–22 indicate two additional riparian habitat themes. Group 19 was included to potentially represent two important functions of riparian vegetation for stabilizing banks and filtering runoff. The group included the extent of cover from undercut banks (retained for PCA) and three mutually correlated indicators of vegetative ground cover on streambanks—the reach-minimum, -mean, and -maximum percentage of streambank coverage by vegetation (*min.BVC*, *BVC*, and *max.BVC*, respectively). Reach-mean values of *BVC* were retained for PCA. Groups 20 through 22 are indicators of light availability. Reach-mean values were selected for the PCA from each of these groups, and for group 21 (channel shading), reach-minimum channel-canopy closure also was retained for PCA because it may control the overall light level produced by scattered sunlight under generally closed canopies.

In addition to removing some redundancy, data reduction also decreased the number of retained variables to no more than 25 percent of the number of sites sampled. In the combined data set for multivariate analyses, there were initially 33 variables and 136 sampling sites (also see sections, "Transformation of Measurement Scales" and "Site Selection").

Transformation of Measurement Scales

Because one description of the multivariate normal distribution is that each variable has a univariate normal distribution for every possible combination of values of the remaining variables, it is logical to inspect each input variable's univariate probability distribution and transform its scale as needed to produce a resulting distribution as nearly normal as possible. If univariate normality could not be achieved adequately by use of mathematical functions, the ordinal ranks were used instead. The specific transformations applied to the measured or calculated values of the habitat variables used for PCA are presented in section, "Multivariate Analysis."

Although virtually all multivariate analytical techniques assume the multivariate normal distribution of the data (that is, multi-dimensional normality), only a few techniques for identifying departures from that assumption are applicable to data sets in which variables may be correlated strongly with each other, but the Henze-Zirkler test does apply (Henze and Zirkler, 1990). The Henze-Zirkler test, as coded for S-Plus (D. Lorenz, USGS, written commun., 2009), was used to calculate the Mahalanobis distance of each data point from the center (corrected for the correlation structure) and to compare the distribution of these distances with their theoretical chi-square distribution. During the testing of multivariate normality, the inclusion of four of the wetland-extent variables became impractical because of their extremely non-normal univariate distributions for which neither functional transformations nor ranks substitution were able to produce acceptable univariate or multivariate normality-test results. These four segment- and reach-level variables (W_{S150}, W_{S50}, W_{R50}, and W_{Rllt}) were excluded from further multivariate analyses.

Site Selection for Multivariate Analyses

Of the 141 sites with reach data from HDAS, five sites were excluded from the multivariate analysis of the combined data set because they lacked data for one or more of the variables selected. The excluded sites include three GCP sites that lacked bankfull width data and two WHMI sites that lacked mid-channel canopy closure data. For the multivariate analyses, it was not critical to retain these sites because a large number of sites were available relative to the number of variables selected.

Principal Component Retention

Among the existing methods for determining how many components are worthy to be retained for interpretation or further analysis is the construction of a scree plot (Cattell, 1966), in which the eigenvalues are plotted in relation to the rank order of the principal components. The smaller eigenvalues, representing random variation or trivial components, tend to lie along a straight line, but at a specific point, the plotted line typically breaks upward for components with large eigenvalues. Cattell (1966) recommended that the components having larger eigenvalues than the break point be retained, but often the scree plot approach is complicated by the lack of a clear break point or the presence of multiple breaks (Jackson, 1993). Mardia and others (1979) point out that using a scree plot criterion typically results in too many included components. A second approach is the broken-stick method (Frontier, 1976; Jackson, 1993), which compares the eigenvalues from the study data with eigenvalues expected from random data. Components are retained if their eigenvalues exceed the corresponding expected value for random data from the broken-stick distribution. A third method, the rule-N approach (Preisendorfer and others, 1981) also uses expected percentages of the total variance that would be expected to be explained by chance alone for each principal component. An important advantage for the rule-N method is the use of confidence intervals to define the chance expectations, based on the number of variables and cases analyzed by the PCA, and specification of the retention threshold in terms of 95-percent confidence rather than simply exceeding the expected (central) value of the distribution of eigenvalues for random data. Thus, the rule-N method requires any retained principal component to have an eigenvalue that exceeds the upper limit of the confidence interval for the corresponding random-data eigenvalue.

Another applicable consideration asks which of the PCA components can be meaningfully retained; that is, in view of the input variables loading highly on the component, it could be interpreted meaningfully. Even when multiple selection methods are considered using a "toolbox" approach, there is clearly some subjectivity and best professional judgment involved in the component selection process (Kachigan, 1986).

For the present study, the scree-plot method did not provide an effective, objective guide for the decision of how many PCA components were needed to preserve the "signal" while minimizing the "noise" content of the data set. Rather, evidence from the broken-stick method, the rule-N method, and interpretability considerations were weighed together in deciding how many principal components were retained.

Rotation Method

The normal varimax criterion for rotation of the principal factors (Kaiser, 1958) was selected to achieve a factor-loadings structure in which each variable is loaded highly on one factor, and all factor loadings either have large absolute values or are near zero. Such a structure has been loosely called "simple structure" (Insightful, 2001). This improved contrast in the loadings structure was expected to aid interpretation of the uncorrelated, rotated factors. Varimax rotation maximizes the sum of the variances of the squared loadings while maintaining the mutual orthogonality of rotated axes (Kaiser, 1958). The factor analysis used the principal factor estimation method (Insightful, 2001) on ordinal ranks of the original values, ranked within each univariate distribution.

Interpretation and Validation

The strength of the loadings of the input variables on each principal component (PC) or factor were used to interpret the relative importance of each resultant factor or component. Additionally, the projections of the original data onto the principal component axes, using the transformation function, are referred to as principal component scores (Insightful, 2001). If the principal components are viewed as indices of the interpreted underlying factors (for example, *PC1* as an index of the relative importance of channel shading by the riparian canopy), then the principal component scores may be viewed as predictions from the fitted principal components model (Insightful, 2001). These predicted values may be summarized statistically and analyzed much as the original data might be. Similarly, factor scores also may be viewed as predicted relative values of interpretable characteristics.

To validate the interpretation of component and factor identity, factor scores for each site were compared with two independent lines of data using rank-correlation tests based on Spearman's *rho* (Helsel and Hirsch, 2002). Neither the solar radiation variables (R_i and R_p) nor LULC variables such as grassland extent had been used for the multivariate analyses, and thus were available for validation.

Linear Regression

Multiple linear regression models were fitted in selected instances to aid in interpreting relations between a response variable and multiple habitat variables. If a multiple-regression model included an interaction term, then both (or all) interacting variables were included as individual terms for completeness, even where one (or more) of the individual variables was a nonsignificant term. For each multiple-regression model, standard diagnostic plots of the residuals were reviewed to ensure there were no indications of gross violation of the assumptions of ordinary least-squares (LS) multiple regression (Kachigan, 1986). The relative importance of the included independent variables was based on partial regression coefficient estimates for models that used variables transformed to their standardized *z*-score form (eq. 1).

The variation of the response variable about the estimated regression line is assessed using the standard error of estimate (SEE), which, as Kachigan (1986) points out, can be considered as a standard deviation of the residual errors about the regression at any point. The multiple-regression R^2, sometimes called the coefficient of determination, represents the proportion of the variance in the dependent (or response) variable that is accounted for by the regression equation. The authors adjusted the multiple-regression R^2 to account for the degree of inflation caused by random chance. Degree of inflation is proportional to the ratio of the total number of included variables to the total number of observational units (number of sites, in this case).

Graphical Summaries

Statistically based graphical summaries were used to construct illustrations. For fitting smooth curves through sets of data points, local regression methods were used, in addition to ordinary LS regression methods already described. Local regression routines are implemented as locally weighted, low-degree polynomial regression using the LOESS method (Cleveland and Devlin, 1988; Insightful Corp., 2005), included within the S-Plus system. But for first-degree (linear) local regression, as the authors specified for this report, LOESS is synonymous with the LOWESS smooth (Cleveland, 1979).

Riparian and Associated Habitat Characteristics

In the following subsections, selected riparian-habitat characteristics of each study area are summarized and descriptively compared (**first report purpose** [question A]). The presentation follows a general order from coarsest to finest spatial detail. Statistical comparisons are presented for selected reach-level characteristics.

Study-Unit Summaries and Comparisons

Basin-Level Characteristics

To address the effects of scale on indicators of riparian character, variables were included that represent the entire drainage area to (1) examine cumulative effects of LULC on water quality (as did Dodds and Oakes, 2008); and (2) serve as a point of reference for comparison with the coarsest summaries of riparian-buffer habitat characteristics. At the basin scale, the habitat variables summarized included indicators of LULC for the total basin and for the riparian buffer along the entire drainage network. Drainage areas ranged from 3.17 to 6,380 km^2, and were more variable across study areas (CV = 257 percent) than within study areas (median CV = 68 percent; table 4).

The LULC for the total drainage basins was highly variable despite the fact that all study areas were located in primarily agricultural settings. The mean percentages of basin area in cropland and pasture (C_b) ranged from 34 to 90 percent among the study areas, and averaged 56 percent overall. Although the CV values for C_b were moderate (28 to 46 percent) for the CNBR, DLMV, and GCP study areas, variability was quite small among WHMI sites (6.6 percent) and quite large among CCYK sites (93 percent). Forest plus woody wetland cover types, when combined, had an average extent of 22 percent at the basin scale, but study-unit means fell into two groups: GCP and DLMV sites had extensive woodland (forest plus woody wetland) cover (50 and 40 percent, respectively), whereas such cover was relatively sparse in the other three study areas' basins (3 to 14 percent). Grassland extent averaged 9.4 percent for all sites, but study-unit cover varied from no grassland in the eastern study areas (DLMV, GCP, and WHMI) to average extents of 9.8 and 37 percent in the CCYK and CNBR, respectively. Differences in natural vegetation account for these contrasts in woodland and grassland extent between eastern and western study areas, except that the WHMI watersheds are located in the Eastern Hardwoods region of natural forest cover.

Within the nominally 90-m buffer zone along the basin drainage network, the land cover mosaic of the riparian zone was more mixed in composition than was the total basin. The extent of cropland and pasture (C_{dnr}) within these riparian zones was attenuated in comparison with total-basin extent (C_b) as indicated by overall means of 44 percent for C_{dnr} and 56 percent for C_b. Mean values of C_{dnr} ranged from 17 to 78 percent among the study areas (table 4). In contrast, the overall mean extent of forest plus woody wetland increased from 22 percent for total basin ($WwWv_b$) to 35 percent for the riparian network ($WwWv_{dnr}$). Within the basin-level riparian buffer area, the study-unit mean values of the woodland indicators (forest extent and forest plus woody wetland extent) ranged from 5.4 to 76 percent and were ordered GCP > DLMV > WHMI > CCYK > CNBR. As was the case for total basin extent, these results are consistent with differences in natural vegetation.

Reach-Level Habitat Characteristics

In regard to hydrogeomorphic characteristics, the studied streams in the CCYK and WHMI study areas typically had longitudinal profiles exhibiting riffle-and-pool morphology, GCP streams had extensive pools, and CNBR and DLMV streams were dominated by runs (table 5). Of the 22 sites that had a reach gradient greater than 5 m/km, 18 were CCYK streams and 3 were WHMI streams. The CCYK and WHMI streams as a group also had significantly greater wetted width (rank-sum $p = 0.0002$) than did the other study areas as a group. Mean bankfull channel width (W_{bf}) was not significantly different between WHMI and CNBR reaches, but W_{bf} at CNBR sites did exceed the other three study areas (rank-sum $p < 0.005$ for each comparison). Stream reaches in the DLMV, GCP, and WHMI study areas had larger width-to-depth (*W:D*) ratios and CV of current velocity (*cv.V*) (rank-sum $p < 0.0001$ for each) but had slower mean current velocity and smaller *Froude* (rank-sum $p < 0.0001$ for each) than did streams in the CCYK and CNBR study areas.

Bank vegetation cover (*BVC*) for CCYK, CNBR, and DLMV reaches was significantly greater than that for GCP and WHMI sites (rank-sum $p \leq 0.007$ for each), but differences between CCYK, CNBR, and DLMV reaches were not significant. Bank shading and canopy openness may explain some bank vegetation differences. Bank canopy closure (CC_b) was significantly greater for streams in the GCP than for streams in any other study area (rank-sum $p < 0.0001$ for each comparison). WHMI sites also had significantly greater CC_b than either CCYK or CNBR (rank-sum $p < 0.006$ for each). Openness of canopy (CA_o) was positively correlated with *BVC* for the CCYK and CNBR study areas, but except for WHMI, this pattern was not duplicated for the eastern study areas.

Table 4. Summary of selected basin- and segment-level physical habitat characteristics, by study area, for sites visited in 2003 or 2004.

[Study area codes: CCYK, Central Columbia Plateau-Yakima River Basin; CNBR, Central Nebraska; DLMV, Delmarva Peninsula; GCP, Georgia Coastal Plain; WHMI, White-Miami River Basins; –, not applicable; m, meter; km^2, square kilometer; <, less than; except where footnoted otherwise, the number of basins summarized was equal to the indicated number of sites]

Characteristic	Symbol	Study area code					Study area code				
		CCYK	CNBR	DLMV	GCP	WHMI	CCYK	CNBR	DLMV	GCP	WHMI
Number of sites	n_s	29	28	25	29	30	–	–	–	–	–
		Study area mean, unless otherwise indicated					Study area coefficient of variation, in percent				
Drainage area, km^2	A_d	652	444	15.0	146	97.6	218	100	57	37	68
Open water bodies, total-basin extent, in percent	OW_b	.42	.62	.14	.53	.24	267	154	146	80	193
Built-up land, total-basin extent, in percent	B_b	1.1	.49	2.9	.90	1.9	84	301	155	137	124
Cropland and pasture, total-basin extent, in percent	C_b	34	58	57	42	90	93	46	28	39	6.6
Row crops, total-basin extent, in percent	Rc_b	4.0	48	41	31	73	259	50	25	37	17
Grassland, total-basin extent, in percent	G_b	9.8	37	0	0	0	94	72	([1])	([1])	([1])
Woody wetland, total-basin extent, in percent	Ww_b	.08	.10	13	7.9	.31	311	417	81	47	111
Forest, total-basin extent, in percent	F_b	14	3.1	27	42	6.8	145	64	49	42	65
Forest plus woody wetland, total-basin extent, in percent	$WwWv_b$	14	3.2	40	50	7.1	144	61	40	31	63
Built-up land, drainage-network riparian buffer, in percent	B_{dnr}	[2]2.0	.28	2.5	.47	1.5	90	213	202	133	142
Cropland and pasture, drainage-network riparian buffer, in percent	C_{dnr}	[2]35	56	33	17	78	87	43	38	66	16
Row crops, drainage-network riparian buffer, in percent	Rc_{dnr}	[2]4.5	41	25	13	54	255	52	39	67	35
Grassland, drainage-network riparian buffer, in percent	G_{dnr}	[2]7.1	35	0	0	0	107	69	([1])	([1])	([1])
Woody wetland, drainage-network riparian buffer, in percent	Ww_{dnr}	[2].21	.16	29	25	1.9	317	263	46	45	108
Forest, drainage-network riparian buffer, in percent	F_{dnr}	[2]16	5.3	33	51	17	136	60	42	34	61
Forest plus woody wetland, drainage-network riparian buffer, in percent	$WwWv_{dnr}$	[2]17	5.4	63	76	19	134	59	21	16	59
Segment length, m	L_S	2,141	2,423	2,542	2,115	1,910	35.1	15.5	19.6	7.7	11.8
Cropland, 50-m buffer distance, segment mean, in percent	C_{S50}	22	26	13	.8	25	128	72	117	384	77
Cropland, 100-m buffer distance, segment mean, in percent	C_{S100}	27	40	21	1.8	39	114	54	61	204	62
Cropland, 150-m buffer distance, segment mean, in percent	C_{S150}	30	47	29	3.0	46	108	45	47	163	56
Cropland, 250-m buffer distance, segment mean, in percent	C_{S250}	32	54	38	6.5	52	104	38	40	120	49
Cropland, longitudinal linear riparian transect, segment mean, in percent	C_{Sllt}	23	25	11	.66	24	135	90	147	480	93

Table 4. Summary of selected basin- and segment-level physical habitat characteristics, by study area, for sites visited in 2003 or 2004—Continued.

[Study area codes: CCYK, Central Columbia Plateau-Yakima River Basin; CNBR, Central Nebraska; DLMV, Delmarva Peninsula; GCP, Georgia Coastal Plain; WHMI, White-Miami River Basins; –, not applicable; m, meter; km^2, square kilometer; <, less than; except where footnoted otherwise, the number of basins summarized was equal to the indicated number of sites]

Characteristic	Symbol	Study area code					Study area code				
		CCYK	CNBR	DLMV	GCP	WHMI	CCYK	CNBR	DLMV	GCP	WHMI
		Study area mean, unless otherwise indicated					Study area coefficient of variation, in percent				
Wetland, 50-m buffer distance, segment mean, in percent	W_{S50}	< 0.05	0	0.86	88	11	530	([1])	460	12	119
Wetland, 100-m buffer distance, segment mean, in percent	W_{S100}	< .05	0	.59	77	6.9	430	([1])	430	19	119
Wetland, 150-m buffer distance, segment mean, in percent	W_{S150}	< .05	< .05	.46	67	5.0	440	530	390	24	121
Wetland, 250-m buffer distance, segment mean, in percent	W_{S250}	< .05	< .05	.34	52	3.3	440	530	320	28	123
Wetland, longitudinal linear riparian transect, segment mean, in percent	W_{Sllt}	0	0	1.0	91	12	([1])	([1])	460	11	125
Woodland, 50-m buffer distance, segment mean, in percent	Wv_{S50}	17	30	77	10.7	58	93	68	26	95	31
Woodland, 100-m buffer distance, segment mean, in percent	Wv_{S100}	13	22	68	20	45	89	74	25	67	41
Woodland, 150-m buffer distance, segment mean, in percent	Wv_{S150}	10.9	18	59	29	39	92	79	29	48	46
Woodland, 250-m buffer distance, segment mean, in percent	Wv_{S250}	9.9	15	50	40	34	115	85	35	31	54
Woodland, longitudinal linear riparian transect, segment mean, in percent	Wv_{Sllt}	17	32	84	7.9	59	106	67	21	118	36
Woodland patch length, longitudinal linear riparian transect, segment mean, m	$Wv_S L_{llt}$	142	110	890	70	240	110	61	88	106	103
Woodland gap frequency, longitudinal linear riparian transect, segment mean, per km	$Wv_S Fg_{llt}$	3.3	2.9	1.8	2.4	6.4	60	54	75	56	41
Combined wetland and woodland, longitudinal linear riparian transect, segment mean, in percent	$WwWv_{Sllt}$	17	32	85	99	71	106	67	21	3.2	30
Combined woodlands, 50-m buffer distance, segment mean, in percent	$WwWv_{S50}$	17	30	78	99	69	93	68	26	3.2	25
Combined woodlands, 100-m buffer distance, segment mean, in percent	$WwWv_{S100}$	13	22	68	98	52	89	74	25	3.8	37
Combined woodlands, 150-m buffer distance, segment mean, in percent	$WwWv_{S150}$	10.9	18	60	96	44	91	79	28	5.2	44
Combined woodlands, 250-m buffer distance, segment mean, in percent	$WwWv_{S250}$	10.0	15	50	92	37	114	85	34	8.6	52

[1]No variance associated with the measured values; actual CV is undefined.

[2]Only 28 basins had a calculated value for this variable.

Table 5. Summary of selected reach-level physical habitat characteristics, by study area, for sites visited in 2003 or 2004.

[Study area codes: CCYK, Central Columbia Plateau-Yakima River Basin; CNBR, Central Nebraska; DLMV, Delmarva Peninsula; GCP, Georgia Coastal Plain; WHMI, White-Miami River Basins; –, not applicable; m, meter; km, kilometer; m/km, meters per kilometer; min., minimum; max., maximum; CV, coefficient of variation; cm/s, centimeters per second; MJ m^{-2} d^{-1}, megajoules per square meter per day; deg. C, degrees Celsius; except where footnoted otherwise, the number of reaches summarized was equal to the indicated number of sites]

Characteristic	Symbol	Study area code					Study area code				
		CCYK	CNBR	DLMV	GCP	WHMI	CCYK	CNBR	DLMV	GCP	WHMI
Number of sites	n_s	29	28	25	29	30	–	–	–	–	–
Earliest day of sampling, day of the year	$min.t_J$	223	202	166	135	198	–	–	–	–	–
Latest day of sampling, day of the year	$max.t_J$	268	218	299	198	232	–	–	–	–	–
		Study area mean, unless otherwise indicated					Study area coefficient of variation, in percent				
Reach length, m	L_R	176	161	146	152	197	51	24.5	9.9	6.1	32
Gradient, m/km	S_w	7.6	1.1	1.9	.86	2.3	97	56	130	59	108
Wetted width, min., m	$min.W_w$	4.9	4.0	2.6	3.6	5.2	142	43	63	51	44
Wetted width, mean, m	W_w	7.2	5.8	3.6	5.6	9.4	130	43	43	35	32
Wetted width, max., m	$max.W_w$	10.3	8.6	4.8	7.9	13.8	117	44	38	29	35
CV of wetted width, in percent	$cv.W_w$	25	24	20	26	28	68	40	46	51	41
Water depth, mean, cm	D_w	46	40	22	36	21	75	60	47	40	51
Width-to-depth ratio, mean, m/m	$W{:}D_w$	23	22	23	20	69	95	101	41	29	57
Bankfull width, min., m	$min.W_{bf}$	8.2	10.4	5.7	[4]7.2	11.8	114	50	50	22	32
Bankfull width, mean, m	W_{bf}	11.4	13.6	6.9	[4]9.5	14.6	97	50	35	22	30
Bankfull width, max., m	$max.W_{bf}$	19.8	18.5	8.3	[4]12.8	18.6	132	55	24	33	31
Width-to-depth ratio, bankfull, mean, m/m	$W{:}D_{bf}$	9.5	6.7	7.6	[4]6.7	12.0	63	47	83	36	32
Flow velocity, min., cm/s	$min.V$	8.5	2.8	.53	1.1	.12	179	174	302	181	550
Flow velocity, mean, cm/s	V	38	21	12	10.6	6.4	80	49	48	81	106
Flow velocity, max., cm/s	$max.V$	82	41	30	28	36	59	40	44	74	72
CV of flow velocity, in percent	$cv.V$	73	50	94	96	[2]158	63	40	116	67	35
Froude number, mean, dimensionless	*Froude*	.19	.12	.086	.057	[2].048	78	54	50	83	82
Pools, relative extent, in percent	*Pool.p*	12	6.3	0	28	13	134	301	([3])	130	149
Riffles, relative extent, in percent	*Riff.p*	20	0	.4	.88	18	89	([3])	500	302	94
Runs, relative extent, in percent	*Run.p*	68	94	99.6	71	69	40	20	2.0	52	31
Bank vegetative ground cover, min., in percent	*min.BVC*	25	13	19	3.3	8.0	145	122	173	137	61
Bank vegetative ground cover, mean, in percent	*BVC*	62	56	57	21	30	41	28	57	68	30
Bank vegetative ground cover, max., in percent	*max.BVC*	93	91	84	61	73	9.6	13	24	47	25
Number of cover-type sampling points, min. – max.	–	25 – 55	54 – 55	12 – 51	50 – 55	50 – 55	–	–	–	–	–
Number of cover-type sampling transects, min. – max.	–	5 – 11	11 – 11	4 – 11	10 – 11	11 – 11	–	–	–	–	–

Table 5. Summary of selected reach-level physical habitat characteristics, by study area, for sites visited in 2003 or 2004—Continued.

[Study area codes: CCYK, Central Columbia Plateau-Yakima River Basin; CNBR, Central Nebraska; DLMV, Delmarva Peninsula; GCP, Georgia Coastal Plain; WHMI, White-Miami River Basins; –, not applicable; m, meter; km, kilometer; m/km, meters per kilometer; min., minimum; max., maximum; CV, coefficient of variation; cm/s, centimeters per second; MJ m^{-2} d^{-1}, megajoules per square meter per day; deg. C, degrees Celsius; except where footnoted otherwise, the number of reaches summarized was equal to the indicated number of sites]

Characteristic	Symbol	Study area code					Study area code				
		CCYK	CNBR	DLMV	GCP	WHMI	CCYK	CNBR	DLMV	GCP	WHMI
		Study area mean, unless otherwise indicated					Study area coefficient of variation, in percent				
Extent of aquatic macrophyte cover, percent	*CvrMp*	15	11	20	1.0	4.2	161	225	158	377	150
Extent of overhanging vegetation cover, percent	*CvrOv*	32	38	2.8	55	5.6	52	52	173	63	95
Extent of undercut bank cover, percent	*CvrUb*	8.8	30	.4	13	10.6	181	84	347	109	100
Extent of woody debris cover, percent	*CvrWd*	4.5	22	15	58	24	153	87	113	41	52
Extent of bank canopy closure, min., percent	$min.CC_b$	13	12	36	65	21	202	173	86	34	118
Extent of bank canopy closure, mean, percent	CC_b	61	64	68	95	82	46	42	41	3.4	15
Extent of bank canopy closure, max., percent	$max.CC_b$	98	96	89	100	100	9.4	16	20	([3])	([3])
Extent of channel canopy closure, min., percent	$min.CC_c$	2.6	2.5	31	54	[1]20	384	446	89	44	139
Extent of channel canopy closure, mean, percent	CC_c	23	28	61	88	[1]69	140	91	51	9.1	28
Extent of channel canopy closure, max., percent	$max.CC_c$	47	71	80	99.8	[1]99.6	100	54	37	1.1	1.5
Open canopy angle, min., degrees	$min.CA_o$	80	43	14.7	0	2.0	79	109	247	([3])	326
Open canopy angle, mean, degrees	CA_o	113	82	30	6.2	27	43	51	134	104	70
Open canopy angle, max., degrees	$max.CA_o$	145	119	61.9	33.0	71.6	20	28	92	61	47
CV of open canopy angle, percent	$cv.CA_o$	40	49	91	202	113	136	101	118	53	53
Potential solar radiation, min., percent	$min.R_p$	[1]58.5	42.0	[5]21.9	2.0	[1]6.3	70	86	175	160	135
Potential solar radiation, mean, percent	R_p	[1]73.2	64.6	[5]27.6	10.7	[1]23.6	43	44	137	50	57
Potential solar radiation, max., percent	$max.R_p$	[1]87.8	83.1	[5]36.6	22.1	[1]45.1	22	29	111	51	50
Estimated incident solar radiation, min., MJ m^{-2} d^{-1}	$min.R_i$	[1]12.9	10.3	[5]4.6	.45	[1]1.3	70	86	175	160	138
Estimated incident solar radiation, mean, MJ m^{-2} d^{-1}	R_i	[1]16.1	15.8	[5]5.8	2.4	[1]4.8	43	44	137	50	57
Estimated incident solar radiation, max., MJ m^{-2} d^{-1}	$max.R_i$	[1]19.1	20	[5]7.7	4.9	[1]9.1	28	29	111	51	50
Water temperature, daily minimum, 30-day mean, deg. C	$min.T_{w30}$	[6]15.2	[8]18.5	[7]15.3	14.6	[8]15.8	18	10	8.6	9.0	7.4
Water temperature, daily mean, 30-day mean, deg. C	T_{w30}	[6]19.1	[8]24.5	[7]19.0	19.5	[8]20.1	14	7.3	12	3.1	5.1
Water temperature, daily maximum, 30-day mean, deg. C	$max.T_{w30}$	[6]23.9	[8]30.8	[7]25.3	23.0	[8]25.0	16	11	18	4.3	6.2
Water temperature, CV of daily means, 30-day period, in percent	$cv.T_{w30}$	[6]4.7	[8]5.3	[7]8.1	8.0	[8]8.7	34	15	22	19	14
Water temperature, daily minimum, 60-day mean, deg. C	$min.T_{w60}$	[6]13.8	[8]13.2	[7]13.0	12.7	[8]15.5	21	16	25	9.5	7.4

Table 5. Summary of selected reach-level physical habitat characteristics, by study area, for sites visited in 2003 or 2004—Continued.

[Study area codes: CCYK, Central Columbia Plateau-Yakima River Basin; CNBR, Central Nebraska; DLMV, Delmarva Peninsula; GCP, Georgia Coastal Plain; WHMI, White-Miami River Basins; –, not applicable; m, meter; km, kilometer; m/km, meters per kilometer; min., minimum; max., maximum; CV, coefficient of variation; cm/s, centimeters per second; MJ m^{-2} d^{-1}, megajoules per square meter per day; deg. C, degrees Celsius; except where footnoted otherwise, the number of reaches summarized was equal to the indicated number of sites]

Characteristic	Symbol	Study area code					Study area code				
		CCYK	CNBR	DLMV	GCP	WHMI	CCYK	CNBR	DLMV	GCP	WHMI
		Study area mean, unless otherwise indicated					Study area coefficient of variation, in percent				
Water temperature, daily mean, 60-day mean, deg. C	T_{w60}	[6]19.0	[8]22.3	[7]19.0	18.5	[8]20.5	14	8.1	12	3.6	5.4
Water temperature, daily maximum, 60-day mean, deg. C	$max.T_{w60}$	[6]24.2	[8]30.9	[7]28.4	23.0	[8]26.0	16	11	20	4.3	6.9
Water temperature, CV of daily means, 60-day period, in percent	$cv.T_{w60}$	[6]5.5	[8]12	[7]8.9	12	[8]8.6	27	18	24	17	12
Cropland land cover, 25-m buffer distance, mean, percent	C_{R25}	8.7	11	7.5	0	7.4	187	132	238	([3])	125
Cropland land cover, 50-m buffer distance, mean, percent	C_{R50}	15	27	9.8	.2	21	167	89	196	540	93
Cropland land cover, longitudinal linear riparian transect, mean, percent	C_{Rllt}	14	25	8.7	0	19	194	123	194	([3])	116
Wetland land cover, 25-m buffer distance, mean, percent	W_{R25}	0	0	0	95	16	([3])	([3])	([3])	13	172
Wetland land cover, 50-m buffer distance, mean, percent	W_{R50}	< .001	0	.14	90	14	540	([3])	500	15	173
Wetland land cover, longitudinal linear riparian transect, mean, percent	W_{Rllt}	0	0	0	93	14	([3])	([3])	([3])	15	181
Woodland land cover, 25-m buffer distance, mean, percent	Wv_{R25}	29	44	81	4.5	74	102	72	38	264	33
Woodland land cover, 50-m buffer distance, mean, percent	Wv_{R50}	22	32	82	8.5	58	95	75	31	151	34
Woodland land cover, longitudinal linear riparian transect, percent	Wv_{Rllt}	21	33	79	5.7	59	130	91	35	219	44
Woodland patch length, longitudinal linear riparian transect, mean, m	Wv_RL_{llt}	86	56	134	14	101	111	96	28	237	64
Woodland gap frequency, longitudinal linear riparian transect, mean, per km	Wv_RFg_{llt}	6.1	7.3	2.4	14	11	76	43	81	22	62

[1]Only 28 reaches had a calculated value for this variable.

[2]Only 29 reaches had a calculated value for this variable.

[3]No variance associated with the measured values; actual CV is undefined.

[4]Only 26 reaches had a calculated value for this variable.

[5]Only 23 reaches had a calculated value for this variable.

[6]Only 24 reaches had a calculated value for this variable.

[7]Only 17 reaches had a calculated value for this variable.

[8]Only 27 reaches had a calculated value for this variable.

GCP reaches also had significantly more channel shading (CC_c) than reaches in any other study area (rank-sum $p \leq 0.0001$), but GCP and DLMV sites did not differ significantly in regard to solar radiation (R_i, R_p) or CA_o. The stream channels of the CCYK and CNBR study areas were significantly less shaded than the eastern streams (rank-sum $p < 0.0001$ for CC_c, $max.CC_c$, CA_o, $max.CA_o$, R_i, R_p, and $max.R_p$). CCYK and CNBR reaches generally were similar in their channel shading (CC_c, $max.CC_c$, R_i, R_p), but for the open-canopy angle measures, CA_o and $max.CA_o$, CCYK reaches were more open than CNBR reaches (rank-sum $p < 0.012$). Despite their lower latitude, GCP sites had significantly smaller values of insolation—R_i (rank-sum $p = 0.0002$) and R_p (rank-sum $p < 0.0001$)—than did WHMI reaches.

Representativeness of Sampled Reaches

The only riparian habitat variables measured for the NEET study at both reach and segment scales were the extent of LULC classes and the length and frequency of patches and gaps in the woodland class. Thus, the question of whether the sampled reaches were representative of the longer segments in which they occur was considered only in terms of riparian LULC variables.

Results from the comparison of the percentage of cropland and woodland cover types within the 50-m buffer zone along reaches with that along segments are listed in table 6. Results from the signed-ranks test for cropland indicated that the median values of reach-level cropland extent (C_{R50}) might be unrepresentative of the segment-level cropland extent (C_{S50}). Results based on the data from the longitudinal transect at 15 m from the streambank (not listed) were similar to those listed for cropland extent within the 50-m buffer zone—the difference between reach- and segment-level estimates was significant for the CCYK sites and for the combined data from all study areas (signed-ranks $p = 0.041$ and $p = 0.0098$, respectively). Within these narrow riparian buffers, cropland generally was a minor land-cover component, composing a highly variable percentage of the buffer area (except for GCP sites, where C_{R50} ranged only from 0 to 6.2 percent; and C_{S50} ranged from 0 to 16.6 percent).

Results from the signed-ranks test for woodland extent indicated that, for either the area bounded by the 50-m buffer (table 6) or that sampled by the longitudinal transect offset 15 m from the streambank (not listed), the median values of reach- and segment-level woodland extent were not significantly different. In contrast, the signed ranks comparisons for woodland gap length, gap frequency, and patch length provided strong evidence that the spatial pattern of patches at the reach level was different from the segment-level pattern (table 6). All tested differences were significant. These results indicate that the reach length used for this study is not long enough to accurately represent the patch structure that characterizes the riparian areas along small, agricultural streams. Despite finding that the reach length used for this study was generally long enough to represent the woodland extent that characterizes the riparian areas, future investigators may need to sample longer reaches or supplement field sampling with analyses of aerial photography to more accurately characterize the riparian corridor in regard to minor cover types and patch structure.

Reach-Level Land Use and Land Cover

In table 7, results indicated that cropland was absent from 75 percent of GCP riparian zones, the interquartile range of cropland extended from 2 to at least 33 percent in the CNBR and WHMI riparian areas, and riparian cropland extent was intermediate for the CCYK and DLMV study areas. Grassland was absent in at least 75 percent of sampled DLMV, GCP, and WHMI riparian zones, whereas in the CCYK and CNBR study areas the median extent ranged from 6 to 32 percent (table 7). In central Nebraska, grassland is the natural vegetation of this Great Plains study area; however, the difference between the CCYK and CNBR reach-level values for riparian grassland extent (G_{R50}) was not significant ($p = 0.058$) because site-to-site variability was great for both study areas. Shrubland was present only in riparian buffers of the CCYK study area, which has the most arid climate of those areas studied.

Wetlands were absent from at least 75 percent of CCYK, CNBR, and DLMV riparian zones, whereas in the WHMI study area they were present at 10 sites (one-third). For the GCP sites, woody wetlands are the natural riparian vegetation of this Coastal Plain study area, and the difference between all other study areas and the GCP in reach-level values for wetlands extent (W_{R50}) was highly significant ($p < 0.0001$). Results in table 7 indicate that woodland (exclusive of woody wetland) typically covered less than 4 percent of GCP riparian zones, more than 55 percent of DLMV and WHMI riparian areas, and 20 to 32 percent for the CCYK and CNBR study areas.

As already noted, woody wetlands were extensive among the GCP sites whereas the woodland cover type occurred relatively infrequently. The sum of the extent of woodland plus wetland was examined as an additional riparian LULC characteristic. When these two cover types were considered as one combined class ($WwWv_{R50}$), the GCP riparian zones were most extensively wooded, followed by the DLMV and WHMI riparian areas (table 7). The CCYK and CNBR study areas had less than 32 percent coverage at most sites. The difference between the CCYK and CNBR sites with respect to this combined cover class was not significant ($p = 0.088$), whereas each of the other pairwise study-unit differences was significant ($p < 0.011$).

Table 6. Summary of results of signed-ranks test for difference between reach- and segment-level indicators of land cover in the riparian area delimited by a fixed-width buffer distance from the stream centerline.

[CCYK, Central Columbia Plateau-Yakima River Basin; CNBR, Central Nebraska; DLMV, Delmarva Peninsula; GCP, Georgia Coastal Plain; WHMI, White-Miami River Basins; *p*-value is probability of the corresponding test statistic resulting under the null hypothesis of no real difference. Statistical significance (*p*-value) of test for difference: From the signed-ranks test (Helsel and Hirsch, 2002)]

Study area	Fixed-width buffer distance from the stream, in meters	Number of sites sampled	Median value of reach-level land-cover indicator	Median value of segment-level land-cover indicator	Statistical significance (*p*-value) of test for difference
Cropland extent, in percent of riparian buffer					
All study areas combined	50	141	0.47	7.2	0.0098
CCYK	50	29	0	4.5	.041
CNBR	50	28	22	24	.793
DLMV	50	25	.72	5.3	.148
GCP	50	29	0	0	.117
WHMI	50	30	19	24	.237
Woodland extent, in percent of riparian buffer					
All study areas combined	50	141	38.1	32.9	0.288
CCYK	50	29	20.3	11.6	.176
CNBR	50	28	31.1	30.0	.624
DLMV	50	25	90.8	80.4	.207
GCP	50	29	3.9	7.6	.461
WHMI	50	30	55.7	54.8	.853
Woodland gap length, in meters					
All study areas combined	15	141	71	159	< 0.0001
CCYK	15	29	47	130	.0001
CNBR	15	28	86	217	< .0001
DLMV	15	25	0	53	.0022
GCP	15	29	149	1,010	< .0001
WHMI	15	30	61	109	.0002
Woodland gap frequency, number per stream kilometer					
All study areas combined	15	141	6.8	2.9	< 0.0001
CCYK	15	29	5.0	3.2	.0053
CNBR	15	28	6.8	2.8	< .0001
DLMV	15	25	1.8	1.3	.0004
GCP	15	29	13	2.0	< .0001
WHMI	15	30	12	6.5	.0005
Woodland patch length, in meters					
All study areas combined	15	141	65	126	< 0.0001
CCYK	15	29	66	111	.0104
CNBR	15	28	45	104	.0007
DLMV	15	25	148	698	< .0001
GCP	15	29	0	54	< .0001
WHMI	15	30	75	159	.0001

Table 7. Statistical summary by study area for relative extent of land cover in the reach-level riparian area delimited by a 50-meter buffer distance from the stream centerline.

[CCYK, Central Columbia Plateau-Yakima River Basin; CNBR, Central Nebraska; DLMV, Delmarva Peninsula; GCP, Georgia Coastal Plain; WHMI, White-Miami River Basins; –, not determined. Statistically significant differences: From the rank-sum test (Wilcoxon, 1945); summary units sharing the same letter for one cover type were not significantly different at the 95-percent confidence level (α = 0.05)]

Study area	Indicated extreme or percentile value of land-cover extent, as a percentage of riparian buffer area						
	Number of sites sampled	Minimum	25th percentile	50th percentile (median)	75th percentile	Maximum	Statistically significant differences
				Cropland			
All study areas combined	141	0	0	0.5	24.2	81.7	–
CCYK	29	0	0	0	18.1	73.1	B
CNBR	28	0	2.4	21.7	47.5	73.8	C
DLMV	25	0	0	.7	6.2	81.7	B
GCP	29	0	0	0	0	6.2	A
WHMI	30	0	2.8	16.5	32.8	61.9	C
				Grassland			
All study areas combined	141	0	0	0	10.0	100	–
CCYK	29	0	0	5.9	25.2	100	B
CNBR	28	0	2.0	32.4	56.4	100	B
DLMV	25	0	0	0	0	25.9	A
GCP	29	0	0	0	0	0	A
WHMI	30	0	0	0	0	1.8	A
				Shrubland			
All study areas combined	141	0	0	0	0	73.0	–
CCYK	29	0	0	27.1	46.3	73.0	B
CNBR	28	0	0	0	0	0	A
DLMV	25	0	0	0	0	0	A
GCP	29	0	0	0	0	0	A
WHMI	30	0	0	0	0	0	A
				Wetland			
All study areas combined	141	0	0	0	27.4	100	–
CCYK	29	0	0	0	0	0	B
CNBR	28	0	0	0	0	0	B
DLMV	25	0	0	0	0	3.6	B
GCP	29	42.8	87.0	95.3	100	100	A
WHMI	30	0	0	0	25.5	89.0	C
				Woodland			
All study areas combined	141	0	0	0	0	0	–
CCYK	29	0	0	20.3	39.6	77.6	B
CNBR	28	0	14.9	32.0	46.3	87.7	B
DLMV	25	0	73.8	90.8	99.2	100	D
GCP	29	0	0	3.9	12.9	57.2	A
WHMI	30	8.7	46.8	55.7	71.7	99.7	C

Table 7. Statistical summary by study area for relative extent of land cover in the reach-level riparian area delimited by a 50-meter buffer distance from the stream centerline—Continued.

[CCYK, Central Columbia Plateau-Yakima River Basin; CNBR, Central Nebraska; DLMV, Delmarva Peninsula; GCP, Georgia Coastal Plain; WHMI, White-Miami River Basins; –, not determined. Statistically significant differences: From the rank-sum test (Wilcoxon, 1945); summary units sharing the same letter for one cover type were not significantly different at the 95-percent confidence level (α = 0.05)]

Study area	Indicated extreme or percentile value of land-cover extent, as a percentage of riparian buffer area						
	Number of sites sampled	Minimum	25th percentile	50th percentile (median)	75th percentile	Maximum	Statistically significant differences
Combined extent of wetland and woodland							
All study areas combined	141	0	31.4	66.5	98.7	100	–
CCYK	29	0	0	20.3	39.6	77.6	B
CNBR	28	0	14.9	31.1	46.3	87.7	B
DLMV	25	0	73.8	90.8	99.1	100	D
GCP	29	88.0	100	100	100	100	A
WHMI	30	39.9	56.5	72.6	86.7	99.6	C

Spatial Scale Effects on Riparian Land-Cover Indicators

Although much emphasis has been placed on the importance of riparian buffers composed of woodland or grassland, the authors recognized that mixtures of disparate land-cover types commonly occur along riparian areas. Not only the dominant land-cover type but also its patchiness and the relative dominance of other cover types were expected to affect algal-nutrient relations in small agricultural streams. In this section of the report, the authors examine how LULC variables and their relations with algal-nutrient responses vary at different spatial scales (**second report purpose** [question B]).

Correlations between cropland extent for the total basin and cropland extent within varying riparian buffer areas were examined at three spatial scales. Correlation strength was weakest for the narrow reach-level buffers (*rho* ≤ 0.11) and increased steadily as buffer area widened and scale increased to segment-level and finally drainage-network scale (*rho* = 0.895) (fig. 2). The rank-correlation coefficient more than doubled between the segment and drainage-network level, approximately doubled between the 25- and 50-m buffer width at the reach scale, and increased by about 50 percent or more between the reach and segment scales.

Results from identical analyses of scale-related patterns of correlation coefficients also are shown in figure 2 for grassland and combined woodland and woody wetland. For grassland, Spearman's *rho* increased by about 50 percent between reach- and segment-level comparisons with basin extent of grassland, and approximately doubled between the segment and drainage-network level. Thus, the patterns for cropland and grassland were generally similar for the three major levels of scale considered; however, for combined woodland the results were quite different. Riparian woodland extent was correlated strongly with its total-basin extent at all levels of the spatial hierarchy, and so the percentage increases in *rho* were relatively small as scale of comparison moved from reach to segment to drainage-network level. To the extent that riparian woodland is the most important LULC type affecting algal-nutrient relations, the pattern of rank correlations indicates that basin characteristics might be effective surrogate predictors of riparian effects, particularly at the drainage-network scale. But to the extent that riparian cropland also is important, the results indicate a much less optimistic expectation for basin-level cropland as a surrogate, at least for the variety of watersheds included in this study.

Further correlations of the extent of riparian woodland examined comparisons among multiple longitudinal bands along the streams (table 8). These results are organized by hierarchical level of habitat assessment and by the riparian buffer summary area or band, as measured from the channel margin. The correlations with woodland extent within 50 m of the channel (reach- and segment-level data) decreased in strength as the compared area shifted beyond the first 50 m from the channel, becoming negligible for areas beyond 100 m from the channel. This pattern contrasted with the increasing strength of correlations with total-basin woodland extent as the compared area shifted from the 50 m nearest to the channel (weak correlations, *rho* < 0.1) to the areas beyond 100 m from the channel (strong correlations, *rho* > 0.5).

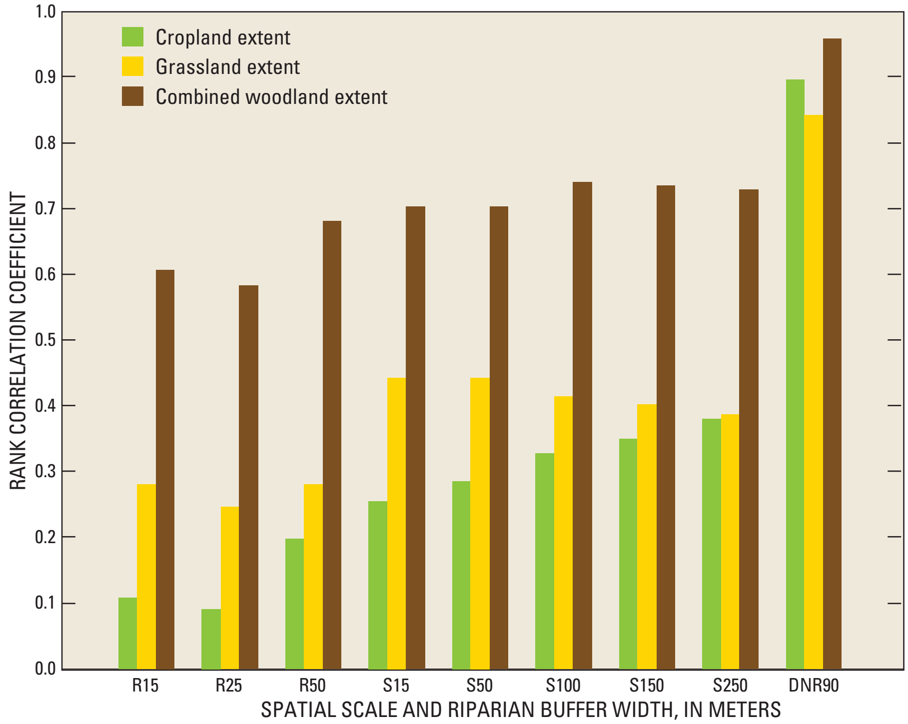

Figure 2. Relation of spatial scale and buffer width to rank correlation strength between total basin extent of principal land uses and their extent in riparian buffers. (Alphanumeric labels on horizontal axis encode scale as: R, reach scale; S, segment scale; DNR, drainage-network-wide scale; numeric part following scale code is buffer width in meters.)

For sites draining less than 60 km^2 (all study areas included), all woodland-extent variables at the segment level were strongly correlated with each other and with total-basin extent of woodland. In contrast, the strength of correlations of reach-level woodland extent (within 25 m of stream) with segment-level woodland extent decreased rapidly for buffer areas more than 50 m from the stream (table 8). The authors found that for streams draining less than 60 km^2, areas beyond 25 to 50 m from the stream may contain mixtures of riparian and nonriparian vegetation, and reach-mean bankfull width for 75 percent of these streams was less than 11 m. At a distance beyond about two to five channel widths from the active channel of most of these small streams, it is likely that the geomorphic surface is either infrequently flooded or too high to be inundated under the present-day flood hydrology. Because the development of riparian vegetation reflects the history of fluvial disturbances (mainly floods) and nonfluvial disturbances (fire, disease, insect infestations), plant communities on the topographically higher parts of the valley floor are older and may include either typical riparian species or upland species encroaching onto the floodplain (Gregory and others, 1991).

For sites draining more than 200 km^2, the rank-correlation strength of woodland extent within 50 m of the channel with woodland extent in more distal riparian buffers was in some cases stronger than 0.56 (for the area from 50 to 100 m from the channel), but was never stronger than 0.37 for buffer areas beyond 100 m from the channel (table 8). The rank-correlation strength with total-basin woodland extent also was less than 0.37 for buffer areas within 100 m from the channel. Two-thirds of these sites had mean bankfull width between 11 and 56 m. Thus, it appears that a mixture of riparian-typical and atypical or nonriparian vegetation was quite common in areas beyond 100 m (typically 2 to 10 channel widths) from the stream for the largest one-fourth of studied basins. These results also indicate that for many

Table 8. Correlations of the total and riparian extents of woodland for selected riparian buffers, defined by habitat hierarchical level and by riparian-buffer distance.

[Tabled values are Spearman's rank-correlation coefficients. km^2, square kilometers]

Level within stream habitat hierarchy	Riparian buffer distance (meters from channel) or summary area	Riparian buffer summary area, at segment level except where otherwise indicated				
		Reach level, 0–25 meters	0–50 meters	50–100 meters	100–150 meters	150–250 meters
All five study areas combined (141 sites)						
Segment	0–50	0.785	–	–	–	–
Segment	50–100	.326	0.666	–	–	–
Segment	100–150	.013	.339	0.864	–	–
Segment	150–250	-.116	.167	.715	0.933	–
Basin	Total basin, including upland	-.038	.095	.461	.587	0.597
Drainage area less than or equal to 60 km^2 (41 sites)						
Reach	15	0.913	0.745	0.540	0.369	0.276
Segment	15	.723	.967	.804	.666	.561
Segment	0–50	.780	–	–	–	–
Segment	50–100	.455	.794	–	–	–
Segment	100–150	.283	.646	.934	–	–
Segment	150–250	.198	.545	.827	.940	–
Basin	Total basin, including upland	.420	.603	.742	.696	.709
Drainage area greater than 200 km^2 (37 sites)						
Reach	15	0.653	0.428	0.396	0.230	0.122
Segment	15	.471	.955	.567	.329	.247
Segment	0–50	.493	–	–	–	–
Segment	50–100	.138	.596	–	–	–
Segment	100–150	-.045	.366	.877	–	–
Segment	150–250	-.079	.281	.814	.944	–
Basin	Total basin, including upland	.190	.055	.363	.462	.403

of the studied small, agricultural streams, the riparian-buffer LULC mosaic may include a heterogeneous mix of riparian and nonriparian land cover when the summarized buffer area extends more than about 50 to 100 m (2 to 10 channel widths) from the streambank, depending upon basin size. Similarly, Dodds and Oakes (2008) found it difficult to separate the effects of land cover in Kansas riparian ecotones (defined as a 33-m buffer area) from land cover in the whole watershed for small basins (mean size, 280 km^2; range, 19–1,400 km^2), and also suspected that land cover in the buffer areas partly reflected the dominant cover types of the watershed. Additional results summarizing correlations of the total and riparian extents of woodland for selected riparian buffers are listed in appendix 1.

Results from signed-rank tests of the difference between total basin extent and segment-level riparian extent of combined wetland and woodland differed somewhat between study areas. For GCP, CNBR, DLMV, and WHMI streams, the differences were significant ($p < 0.0025$) for all segment-level variables. Among CCYK streams, the differences were not significant ($p > 0.159$) for any of the buffer widths considered except for the 50-m buffer (p=0.042). Similarly, differences between basin-scale and segment-level extents of combined wetland and woodland within the riparian buffer areas were significant ($p < 0.001$) for all segment-level buffer widths among the GCP, CNBR, and WHMI sites. Differences between these same indicators were significant ($p < 0.004$) for buffer widths of up to 50 m and for 250 m in DLMV. Among CCYK streams, the differences were not significant (p>0.17) for any of the buffer widths considered.

The extent of cropland summarized by study area is shown in figures 3*A* and 3*B*. For all study areas, the extent of cropland increased as the analysis buffer width increased. In the CNBR and WHMI study areas, cropland percentage more than doubled as the buffer width increased from 25 to 50 m, whereas lesser increases were noted for the CCYK and DLMV areas. The mean cropland extent in riparian buffers of DLMV sites did not continue to increase between the segment and basin scales, and the difference between basin-level extent (C_{dnr}) and segment-level extent of riparian cropland was significant for the 250-m buffer (C_{S250}) ($p = 0.032$), but not for the 150-m buffer (C_{S150}) (p>0.4) for the DLMV sites.

Signed-rank tests of the difference between total-basin extent and segment-level riparian extent of cropland showed differing results for eastern study areas than for CCYK and CNBR. For DLMV, GCP, and WHMI sites, the differences were significant ($p < 0.0001$) for all segment-level variables. For CNBR sites, the differences were significant ($p < 0.02$) only for buffer widths of up to 100 m, and for CCYK sites, none of the differences were significant (p>0.144). Similarly, the differences between basin and segment-level extents of cropland within the riparian buffer areas were significant ($p \leq 0.0001$) for all segment-level buffer widths among the GCP and WHMI sites. But for the CNBR and DLMV sites, the differences were significant ($p < 0.032$) for buffer widths of up to 100 m, and for CCYK sites none of the differences were significant (p>0.158).

In addition to scale-related patterns within the habitat characteristics, a number of scale effects were noted in the pattern of correlations between LULC variables and response variables. Most such instances are reported within the report section corresponding to the response variable, but a few are given in the following paragraphs as examples.

Two examples from the combined data set are the correlations between *DIN* and either cropland or woodland extent across the varying scales and buffer widths (fig. 4). Correlation coefficients steadily increased with increasing scale and buffer width for *DIN* and cropland, but remained relatively constant for *DIN* and woodland extent for buffer widths up to 50 m. For buffer widths greater than 50 m, correlation coefficients for *DIN* and woodland extent decreased steadily and became negative at the basin scale.

Scale-related patterns of correlations also were found for relations with riparian LULC indicators within individual study areas. One example is the correlation pattern across varying scales and buffer widths in the CCYK between periphyton biovolume (*DBV*) and cropland extent (fig. 5). Results indicated that there was no relation at the basin scale but strong negative correlations for narrow buffers at the reach scale. This pattern may be associated with greater abundance of local sources of fine sediment or agricultural contaminants where cropland predominates the riparian area. Eroded sediment or agricultural contaminants can reduce habitat quality by increasing turbidity, chemical contamination, or burial of periphyton by fresh deposition. Among the WHMI sites, another scale-related pattern was noted in the correlations of total nitrogen concentration with extent of woodland (fig. 5). This relation was inverse for the total basin extent, but correlations became positive for buffer widths up to 50 m at the segment scale. This difference might reflect both the decreased nitrogen loading into streams from basins where woodland is more extensive and the decreased biotic processing of nitrogen in well-shaded segments.

Within three study areas (CCYK, DLMV, and WHMI) there was a strong correlation of aquatic macrophyte or macroalgae cover (*AMp*) with riparian woodland extent. However, each study area's correlation was strong at a scale different from that for the other study areas, and occurred strongly for only one level of the scale hierarchy per study area. Moreover, these correlations were of different signs, being negative for CCYK and DLMV sites, but positive for the WHMI sites. This variability likely includes more than spatial scale effects, and other factors are discussed in section, "Aquatic Macrophytes and Macroalgae." Here, it is simply noted that for DLMV sites, where the correlation with woodland extent was for the reach scale, the correlation was stronger than that in the other study areas and also was consistent with strong correlations with channel shading and light availability. This example illustrates that data for riparian LULC may represent different processes at differing scales, and LULC-biota relations typically are moderated by other habitat factors such as turbidity or substrate.

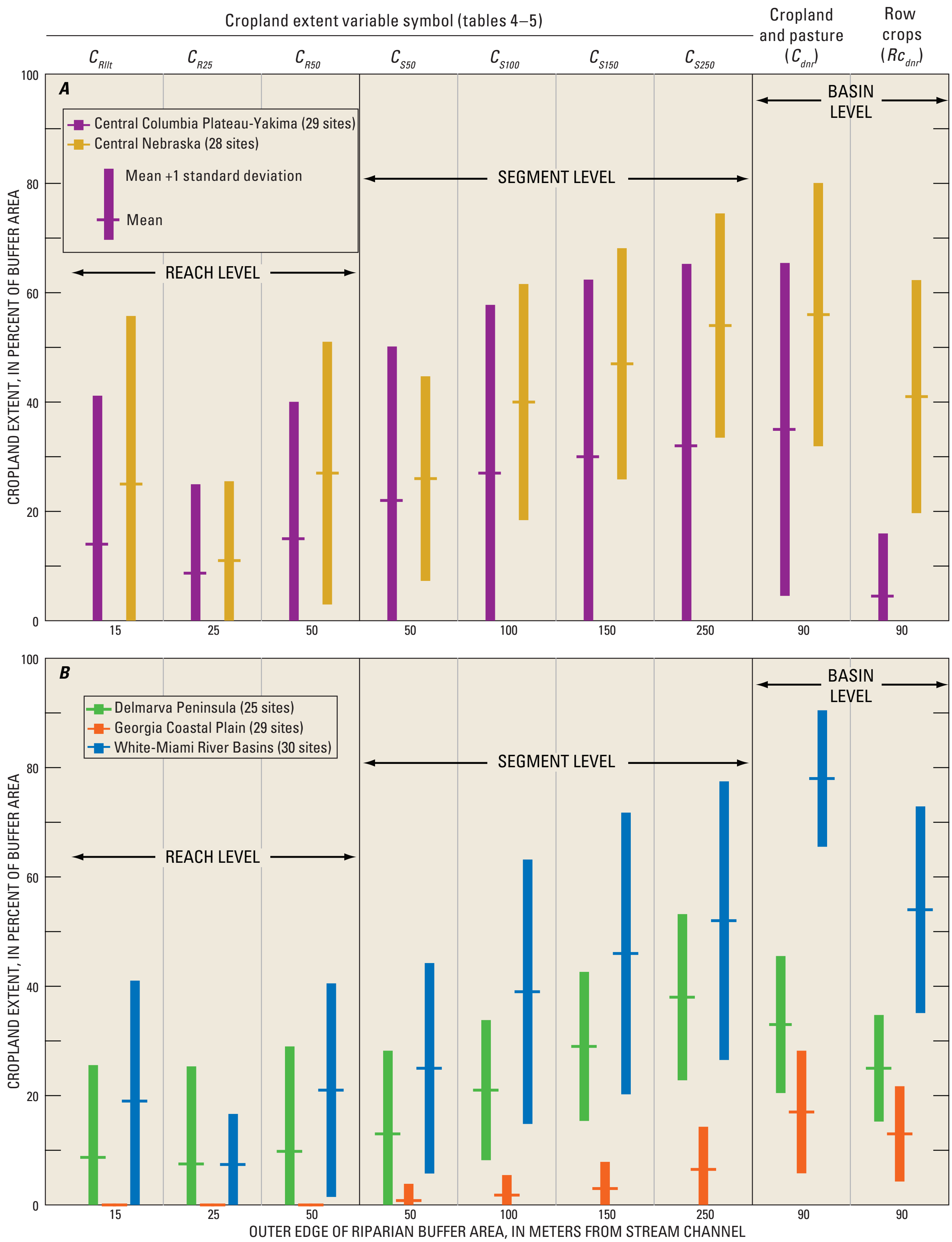

Figure 3. Relation of areal extent of cropland to analysis buffer width, by study area for (*A*) Central Columbia Plateau-Yakima and Central Nebraska study areas, and (*B*) Delmarva Peninsula, Georgia Coastal Plain, and White-Miami River Basins study areas.

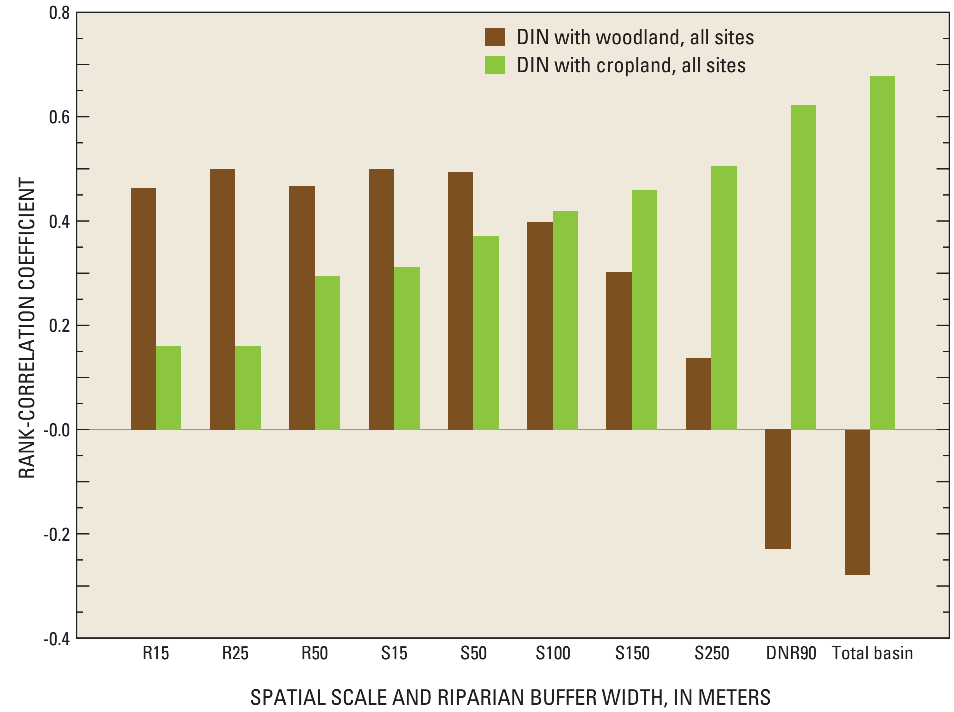

Figure 4. Relations for all sites combined of spatial scale and buffer width to strength of rank correlation between concentration of dissolved inorganic nitrogen (*DIN*) and extent of riparian land uses (cropland and woodland). (Spatial scale [prefix]: R, reach; S, segment; DNR, drainage network-wide riparian buffer; Total basin buffer width not applicable.)

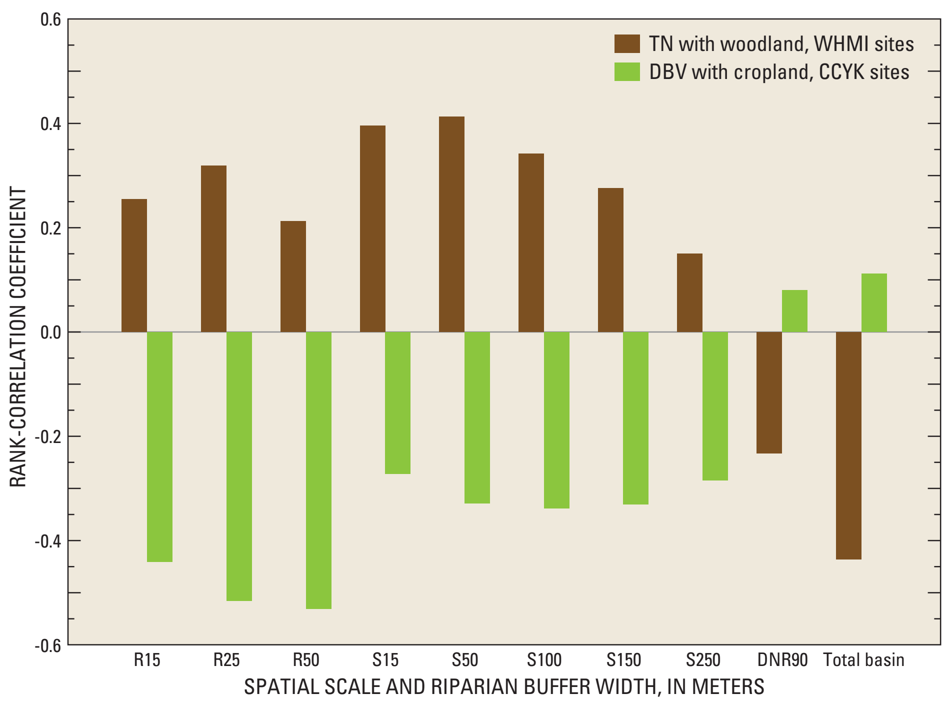

Figure 5. Relations within Central Columbia Plateau-Yakima River Basin (CCYK) and White-Miami River Basins (WHMI) study areas of spatial scale and buffer width to strength of rank correlation between response variables (biovolume in fine-grained benthic habitat [*DBV*] and total nitrogen [*TN*]) and land-use or land-cover extent (cropland and woodland). (Spatial scale [prefix]: R, reach; S, segment; DNR, drainage network-wide riparian buffer; Total basin buffer width not applicable.)

Multivariate Analysis

For the analysis of all sites combined, the Henze-Zirkler test of multivariate normality indicated that there were three outlier points, which were removed from the data set, leaving 133 remaining sites. Diagnostic results suggested that there were no remaining gross violations of multivariate normality. PCA results for the set of 29 selected habitat variables and all study areas indicated that 60.1 percent of the total variance was included within the first four principal components. But scatter plots of the first component (*PC1*) with the second (*PC2*) or third (*PC3*) component indicated that the GCP sites clearly formed a distinct population (fig. 6), particularly with respect to their *PC1* scores. *PC1* had highest loadings from canopy angle and channel canopy closure. The presence of strong bimodality (fig. 6*A*) is a clear violation of the multivariate-normality assumption that underlies PCA, and also illustrates the strength of differences in riparian LULC between GCP and other sites that have been discussed already in relation to the first report objective.

The PCA was re-run using the same set of variables but with all GCP sites excluded. For the analysis of data from all sites combined (for four study areas), the Henze-Zirkler test of multivariate normality indicated that there were five outlier points, which were removed from the data set, leaving 105 remaining sites. Each study area had at least one outlier point thus excluded. PCA results indicated that 60.3 percent of the total variance was included within the first four principal components, and 53.2 percent within the leading three PCs. Results from both the broken-stick and rule-N methods indicated that the first three principal components should be retained to capture the greatest proportion of the total variance without including uninterpretable or random modes of variation. Table 9 summarizes the results for the broken-stick and rule-N methods and lists the percentage of total variance explained by each leading PC.

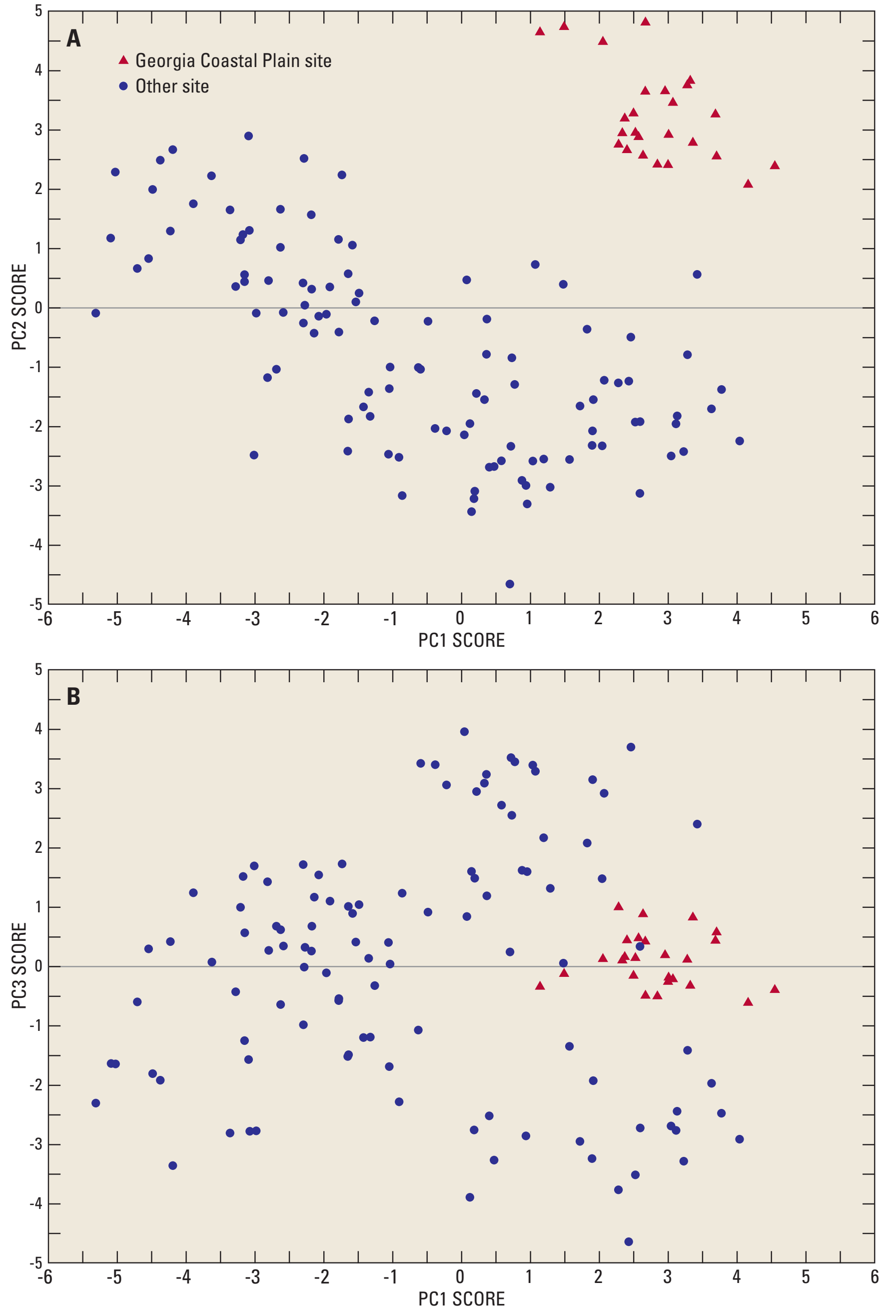

Figure 6. Relations among scores on first three principal components from principal components analysis of data for five study areas.

Table 9. Summary of input variables, transformations, and selected results from principal components and factor analyses of riparian and associated habitat variables.

[PC, principal component; PC*i*, principal component *i*, *i* = 1,2,3; PCA, PC analysis; *F1*, *F2*, *F3* are rotated factors from factor analysis; NTA, no transform applied; GCP, Georgia Coastal Plain study area; n, neutral loading, that is, magnitude less than 0.1; –, not applicable; factor analysis used ranks substitution for all included variables; bold factor loadings were stronger than 10.51 and among the strongest 29 percent of loadings on the respective factor; variable symbol with prime mark indicates that values were transformed using the indicated function]

Variable symbol (tables 4–5)	Univariate transform function	Ranks substituted for final PCA	Included in analyses of 4 and 5 study areas	Included in analyses of GCP study area
Pool.p	NTA	yes	yes	no
Riff.p	NTA	yes	yes	no
$W{:}D_w'$	$\log_{10}(W{:}D_w)$	no	yes	no
$min.W_w'$	$\log_{10}(min.W_w)$	–	no	no
$max.W_w'$	$\log_{10}(max.W_w)$	–	no	no
$cv.W_w'$	$\log_{10}(cv.W_w+1)$	yes	yes	yes
W_{bf}'	$\log_{10}(W_{bf})$	no	yes	no
S_w'	$\log_{10}(S_w)$	yes	yes	no
$min.V'$	$\log_{10}(min.V+0.003)$	yes	yes	no
$Froude'$	$\log_{10}(Froude+0.09)$	no	yes	no
$CvrOv'$	$(CvrOv+3)^{0.5}$	yes	yes	no
$CvrUb'$	$(CvrUb)^{0.5}$	yes	yes	no
$CvrWd'$	$(CvrWd)^{0.5}$	yes	yes	yes
BVC'	$(BVC)^{0.5}$	yes	yes	yes
$min.CC_b'$	$\arcsin(min.CC_b/100)$	–	no	no
CC_b'	$(CC_b+3)^2$	yes	yes	no
$min.CC_c'$	$\log_{10}(min.CC_b+6)$	yes	yes	no
CC_c'	$\arcsin(CC_c/100)$	yes	yes	yes
$max.CC_c'$	$(\arcsin(max.CC_c/100)+0.5)^{3.25}$	–	no	no
$min.CA_o'$	$(min.CA_o+0.5)^{0.25}$	–	no	no
CA_o'	$\log_{10}(CA_o+1)$	yes	yes	no
$cv.CA_o'$	$(cv.CA_o)^{0.5}$	–	no	no
C_b	NTA	yes	yes	yes
C_{S150}	NTA	yes	yes	no
C_{Sllt}'	$(C_{Sllt})^{0.5}$	yes	yes	no
C_{R25}'	$\arcsin(CR_{r25}/100)$	yes	yes	no
Ww_b'	$\arcsin((\log_{10}(Ww_b+0.009)+2.1)/3.8$	yes	yes	no
Ww_{dnr}'	$\arcsin(\log_{10}(Ww_{dnr}+0.1)/2)$	–	no	no
W_{S150}'	$\log_{10}(\arcsin(W_{S150}/100)+0.03)$	no	no	yes
F_b'	$\log_{10}(F_b+0.02)$	yes	yes	no

Symbol	Summary statistic			Value for indicated factor *F1*	*F2*	*F3*
	Factor analysis for GCP study area					
–	Sum of squared loadings			1.663	1.184	0.917
–	Proportion of variance included			.238	.169	.131
–	Cumulative fraction of variance included			.238	.407	.538
	Factor analysis for other four study areas					
–	Sum of squared loadings			7.081	3.585	3.346
–	Proportion of variance included			.244	.124	.115
–	Cumulative fraction of variance included			.244	.368	.483
	Loading on indicated PC *PC1*	*PC2*	*PC3*	Loading on indicated factor *F1*	*F2*	*F3*
	PC analysis for GCP study area			Factor analysis for GCP study area		
Wv_SFg_{llt}	0.583	-0.170	-0.167	**0.7825**	n	0.2379
CC_C	.411	n	.500	.2177	n	**.6569**
C_b	.402	.117	.217	.2213	-.1197	.3699
BVC	-.141	-.618	.252	n	.7169	-.1290
CvrWd	-.119	-.349	-.590	.1610	.1002	**-.5220**
$cv.W_w$	-.191	-.553	.420	n	**.7905**	n
W_{S150}	-.509	.383	.294	**-.9610**	-.0937	n
	PC analysis for other four study areas			Factor analysis for other four study areas		
$W{:}D_w'$	0.2048	-0.1689	-0.3036	0.4625	-0.1278	**0.7066**
W_w'	n	-.2067	-.3174	n	n	**.7050**
$cv.W_w$*	n	n	-.2698	n	-.1639	.4264
W_{bf}'	n	-.1914	-.3285	-.1581	n	**.6845**
*CvrOv**	-.2745	n	n	**-.6920**	.2743	-.1019
*CvrUb**	-.1316	-.2268	n	-.2978	.4597	.1292
*CvrWd**	.1554	-.2361	.1869	.4823	.4867	.1157

Table 9. Summary of input variables, transformations, and selected results from principal components and factor analyses of riparian and associated habitat variables—Cont.

[PC, principal component; PC*i*, principal component *i*, *i* = 1,2,3; PCA, PC analysis; *F1*, *F2*, *F3* are rotated factors from factor analysis; NTA, no transform applied; GCP, Georgia Coastal Plain study area; n, neutral loading, that is, magnitude less than 0.1; –, not applicable; factor analysis used ranks substitution for all included variables; bold factor loadings were stronger than 10.51 and among the strongest 29 percent of loadings on the respective factor; variable symbol with prime mark indicates that values were transformed using the indicated function]

Variable symbol (tables 4–5)	Univariate transform function	Ranks substituted for final PCA	Included in analyses of 4 and 5 study areas	Included in analyses of GCP study area
Wv_{S150}	NTA	yes	yes	no
Wv_{Sllt}	NTA	yes	yes	no
$Wv_{R25}{}'$	arcsine(Wv_{R25}/100)	yes	yes	no
$Wv_SL_{llt}{}'$	$\log_{10}(Wv_SL_{llt}+12)$	yes	yes	no
$Wv_SFg_{llt}{}'$	$(Wv_SL_{llt})^{0.5}$	yes	yes	yes
Wv_RFg_{llt}	NTA	yes	yes	no

Summary statistic	All five study areas	Four study areas	GCP
Number of sites included in multivariate analyses	133	105	26
Number of variables included in multivariate analyses	29	29	7
Number of principal components retained for interpretation	–	3	3
Observed eigenvalue of last retained principal component	–	3.323	1.283
Broken-stick eigenvalue of last retained principal component	–	2.462	1.093
Upper limit of 95-percent confidence interval of rule-N variance explained for last retained PC (percent)	–	7.99	17.98
Variance explained by last retained PC (percent)	–	11.47	18.32
Relative exceedance of rule-N upper limit (percent)[1]	–	43.6	1.9
Total variance explained by retained components (percent)	–	53.2	71.9

Symbol	Loading on indicated PC: *PC1*	*PC2*	*PC3*	Loading on indicated factor: *F1*	*F2*	*F3*
	PC analysis for other four study areas			Factor analysis for other four study areas		
*BVC**	-0.2224	0.1751	n	-0.5739	-0.1355	-0.3528
CC_b*	.1100	-.1503	0.1717	.3453	.3385	n
$min.CC_c$*	.2642	n	.2287	**.7965**	.1800	-.1819
CC_c*	.2788	-.1359	.1900	**.8417**	.3250	n
CA_o*	-.3055	n	-.1674	**-.9057**	-.1823	n
C_{Sllt}*	n	-.2873	.2376	n	**.7134**	n
C_{R25}*	n	-.2190	.1805	-.1121	**.5081**	n
C_{S150}*	n	-.2807	.3010	n	**.7683**	n
Wv_{Sllt}*	.3039	.1008	n	**.7940**	-.3438	n
Wv_{R25}*	.2821	n	n	**.7781**	n	n
Wv_{S150}*	.2878	.1415	n	**.7358**	-.4218	n
Wv_SL_{llt}*	.2428	.2408	n	.6004	**-.6028**	n
Wv_RFg_{llt}*	n	-.3461	n	n	**.5670**	.3675
Wv_SFg_{llt}*	n	-.2967	-.1606	n	.2681	**.5875**
*Pool.p**	n	-.2300	-.2295	n	.1027	**.5772**
*Riff.p**	n	-.1509	-.3017	n	n	**.5431**
S_w*	n	n	-.2234	-.1250	-.2668	.1550
*min.V**	-.2259	.1082	n	-.5530	n	-.3083
Froude´	-.1805	.1726	n	-.3563	n	-.3563
C_b*	.1149	-.1807	n	.2813	.1665	.3312
Ww_b*	.2587	.1565	n	.6810	-.3162	-.1422
F_b*	.2063	.1189	n	.5109	-.2838	n

[1]Value indicates relative strength of inference that last-retained PC explains more than random variation.

*Rank substitution used for final PCA.

Principal Factors

The first three principal components were subsequently rotated to estimate the matrix's most simple (or interpretable) structure (Kaiser, 1958). After varimax rotation, 48.3 percent of the total variance was included in the resulting three-factor model.

In the factor analysis of the data set that included 105 sites (all GCP sites excluded), there were 29 variables retained that had been identified as adequately representing 20 groups of habitat characteristics. The set of variables that loaded strongly on the first three principal factors are the focus of this section, because they directly address the **third report purpose** (question C).

The loadings of the input variables on the first three principal components and factors are listed in table 9. Factor 1 (*F1*) accounted for 24.4 percent of the total variance in the data set. *F1* was interpreted as an index of channel shading. Very strong loadings on *F1* by channel canopy closure (fig. 7), open-canopy angle, and woodland extent within the two narrowest riparian buffers (15- and 25-m buffers at segment and reach levels, respectively) support this interpretation. Factor 1 scores were strongly correlated with all solar radiation variables and other reserved variables, including reach-extrema for open-canopy angle and extent of woody wetland and forest in the basin-level riparian network (table 10). The negative loading on *F1* by overhanging vegetation cover is parallel to the negative correlation between *F1* scores and grassland extent within narrow riparian buffers.

The habitat measures that loaded most strongly on *F1* could be considered the best indicators of riparian canopy shading among the indicators measured for this study. These measures were reach-mean open-canopy angle (CA_o) and channel canopy closure (CC_c). The latter measure was added specifically for this study, supplemental to the standard NAWQA habitat protocol of Fitzpatrick and others (1998). One reason that the standard protocol did not include the mid-channel sampling point for CC_c may be an assumption that stream width of NAWQA ecological sampling sites would be larger than many of those used for the NEET study. Moreover, several of the variables most closely associated with *F1* (for example, percentage of woodland cover within narrow riparian buffers) are not among those routinely measured for physical habitat characterization of NAWQA ecological sampling sites.

Factor 2 (*F2*) explained 12.4 percent of the total variance in the data set. *F2* loadings were largest for two segment-level cropland extent metrics (C_{S150} and C_{Sllt}; table 9). The next strongest loading on *F2* was for another segment-level variable, mean length of patches of riparian woodland along the longitudinal transect ($Wv_S L_{llt}$), which was inversely related to *F2*. Thus, factor 2 appears to meaningfully be

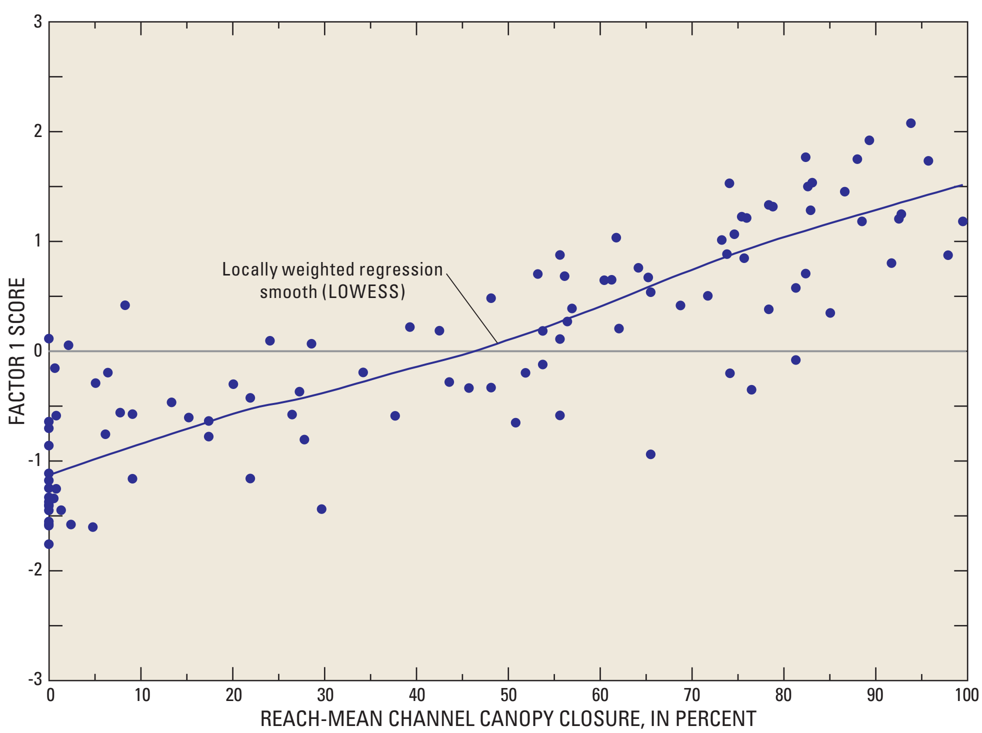

Figure 7. Relation of scores on first principal factor to reach-mean channel canopy closure from factor analysis of data for four study areas (that is, data for Georgia Coastal Plain were excluded because they composed a separable population, or second mode, in multivariate distribution).

an index of cropland within riparian buffers (fig. 8). *F2* scores were not correlated strongly with any of the reserved variables (table 10). Among the variables most strongly related with *F2*, none of these LULC indicators are routinely measured for physical habitat characterization of NAWQA ecological sampling sites. Given that the two leading factors together contained about 37 percent of the total variance in the 29-variable data set, it appears that studies focusing on riparian conditions might benefit from supplementing the standard NAWQA protocol for habitat characterization.

Table 10. Correlations of reserved riparian habitat variables with scores from factor analysis of data for four study units.

[Rank correlation computed as Spearman's *rho* (Helsel and Hirsch, 2002); nc, very weak correlation, that is, magnitude of Spearman's *rho* was less than 0.05; **bold type** indicates strong correlation (|*rho*| > 0.5)]

Habitat variable	Variable symbol	Coefficient of rank correlation with indicated factor scores			Number of sites summarized
		Factor 1 score	Factor 2 score	Factor 3 score	
Solar insolation					
Potential solar radiation, minimum	$min.R_p$	**-0.7620**	-0.2024	-0.0503	103
Potential solar radiation, mean	R_p	**-.8373**	-.2017	nc	103
Potential solar radiation, maximum	$max.R_p$	**-.8310**	-.1628	-.0505	103
Estimated incident solar radiation, minimum	$min.R_i$	**-.7784**	-.1770	nc	103
Estimated incident solar radiation, mean	R_i	**-.8625**	-.1531	nc	103
Estimated incident solar radiation, maximum	$max.R_i$	**-.8296**	nc	-.0613	103
Other reach-level habitat indicators					
Extent of bank canopy closure, reach minimum	$min.CC_b$	0.4822	0.1497	-0.2159	105
Extent of bank canopy closure, reach maximum	$max.CC_b$	-.3764	.3554	.5139	105
Extent of channel canopy closure, reach maximum	$max.CC_c$	.4959	.4037	.3736	105
Open canopy angle, reach minimum	$min.CA_o$	**-.7785**	-.1935	-.1459	105
Open canopy angle, reach maximum	$max.CA_o$	**-.8085**	-.1329	-.0761	105
Open canopy angle, reach CV of transect-level measurements	$cv.CA_o$	**.8265**	.3116	.2081	98
Land-use and land-cover indicators					
Cropland and pasture, drainage-network riparian buffer	C_{dnr}	0.0366	0.3069	0.3628	104
Grassland, total-basin extent	G_b	-.3318	.3229	nc	105
Grassland, drainage-network riparian buffer	G_{dnr}	-.4140	.4496	.1590	104
Grassland, segment-level, extent in 100-m buffer	G_{S100}	**-.7165**	.0568	nc	105
Grassland, segment-level, extent in 50-m buffer	G_{S50}	**-.7140**	.0688	-.0658	105
Grassland, reach-level, extent in 25-m buffer	G_{R25}	**-.5808**	.1026	-.1408	105
Woody wetland, drainage-network riparian buffer	Ww_{dnr}	**.7085**	-.3373	-.0875	104
Forest, drainage-network riparian buffer	F_{dnr}	**.6017**	-.3088	.0541	104

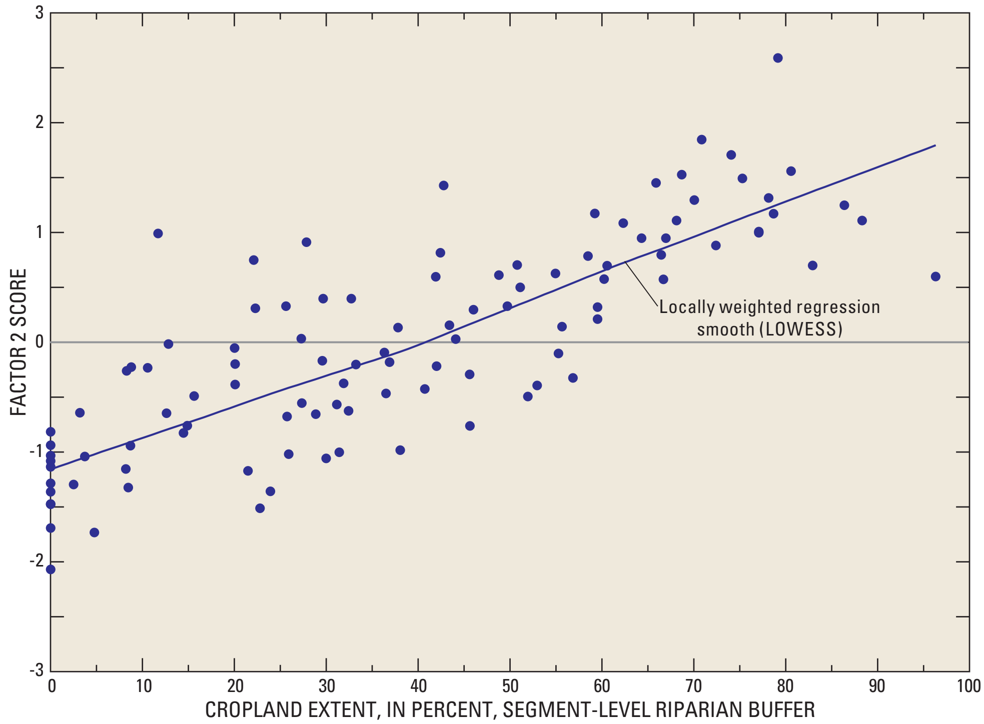

Figure 8. Relation of scores on second principal factor to segment-level extent of cropland within 150-meter riparian buffer from factor analysis of data for four study areas (that is, data for Georgia Coastal Plain were excluded because they composed a separable population, or second mode, in multivariate distribution).

Factor 3, *F3*, included 11.5 percent of the variance, and had very strong loadings from reach-mean width-to-depth ratio ($W{:}D_w$) and mean wetted width (W_w ; table 9). Bankfull channel width (W_{bf}) also had a strong positive loading on *F3*, as did the frequency of gaps in riparian woodland ($Wv_S Fg_{llt}$) and the extent of pool habitat (*Pool.p*). Results listed in table 10 indicate that *F3* scores were correlated strongly with reach-maximum canopy closure, but not with any other of the reserved variables. Reach-mean width-to-depth ratio was the characteristic that loaded most strongly on *F3*, thus factor 3 appears to meaningfully be an index of the width-to-depth ratio (fig. 9), representing the channel shape in profile view. If representative of the segment-level width-to-depth ratio (not measured for this study), *F3* also could relate to the sensitivity of a stream to warming by solar radiation, which typically occurs over a stream length longer than most reaches used for this study.

One LULC basin characteristic (cropland extent) and one riparian variable (bank-canopy closure) did not load strongly on any of the three factors. Two of the reach-level physical habitat variables (stream gradient and Froude number) did not have strong loadings on any of the principal factors. These habitat variables thus were indicated as ancillary or less unique in their contributions to the three principal modes of variation in the selected habitat characteristics, in contrast to the riparian habitat variables that were better represented by the resulting factors.

In summary, the set of variables that appears to best characterize riparian buffers of four study areas included mid-channel measures of canopy shading, riparian cropland extent for the narrow buffer (15 m) and 150-m buffer, and measures of the patchiness of woodland cover in the narrow buffer (patch length and gap frequency). LULC metrics calculated for riparian buffers, particularly at the segment scale, were more correlated with the principal modes of variation in the overall habitat data set than was LULC extent for the total basin drained by each site.

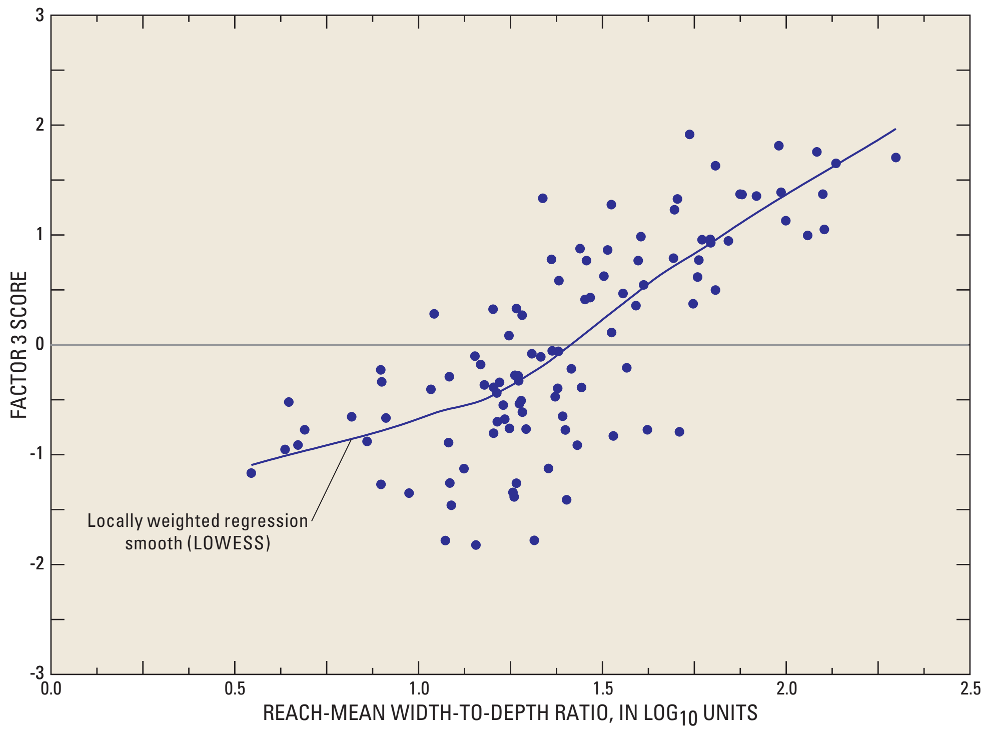

Figure 9. Relation of scores on third principal factor to reach-mean width-to-depth ratio from factor analysis of data for four study areas (that is, data for Georgia Coastal Plain were excluded because they composed a separable population, or second mode, in multivariate distribution).

Principal Components for Georgia Coastal Plain Sites

The previously excluded Georgia sites were examined using a separate PCA of the GCP data set consisting of 26 sites and a subset of the 33 variables. The subset was identified by using smaller PCA runs, one per each of 6 groups of the original 33 variables, and examining the loadings and plots of *PC1* and *PC2* scores ("biplots") from each. The variable groups thus examined were cropland extent, wetland extent, woodland extent, and each of the three themes of reach-level habitat variables that had been measured onsite—in-stream cover, hydrogeomorphic character, and other riparian habitat (as in table 3, except undercut bank extent [*CvrUb*] was moved into the in-stream cover group). For cropland extent there was no variance among GCP sites in values of C_{R25} (all zero), so it was not included in the smaller PCA. Results indicated that C_b was the most representative for the cropland variables group. For wetland extent, results indicated that W_{S150} was the most representative variable. Segment-level frequency of gaps in riparian woodland was most representative for the woodland variables group. Woody debris cover was the strongest of the three candidates from the in-stream cover variables group. Among the hydrogeomorphic variables group, the variability of wetted width (*cv.Ww*) was indicated as the most representative. Finally, the results for the other riparian habitat variables indicated that both channel-canopy closure (CC_c) and bank vegetative cover (*BVC*) were about equally important to best represent this group.

The Henze-Zirkler test of multivariate normality and diagnostic results both indicted that there were no violations of multivariate normality in the GCP data set of 7 variables and 26 sites. PCA for the GCP sites indicated that 53.6 percent of the total variance was included within the first two principal components, and 71.9 percent within the first three. The rule-N method indicated that the first three PCs explained more variance than would be expected by chance. The first three principal components were subsequently rotated to estimate the matrix's most simple structure. After varimax rotation, 53.8 percent of the total variance was included in the resulting three-factor model.

For the GCP sites, factor 1 (*F1*) accounted for 23.8 percent of the total variance in the GCP data set. The loadings of the input variables on the first three principal components and factors are listed in table 9. *F1* was interpreted as an index of segment-level riparian LULC, and in particular, wetland extent. *F1* had a strong negative loading from riparian wetland extent (fig. 10), and a positive loading from segment-scale frequency of gaps in riparian woodland. Neither solar insolation variables nor the other reserved habitat variables were strongly correlated with *F1* scores (appendix 2).

Factor 2 (*F2*) accounted for 16.9 percent of the total variance in the GCP data set. *F2* was interpreted as an index of reach-level variability in wetted width, because *F2* had a strong positive loading from the reach-CV of wetted width ($cv.W_w$; fig. 11). The data also indicated that $cv.W_w$ was related to the wetted width of GCP sites, because reach-mean wetted width (W_w) was negatively correlated with $cv.W_w$ ($rho = 0.634$). None of the reserved variables were strongly correlated with *F2* scores (appendix 2). Factor 3 (*F3*) accounted for 13.1 percent of the total variance in the GCP data set. Channel canopy closure (CC_c) had the largest loading on *F3* (fig. 12) and woody debris cover (*CvrWd*) had a moderate loading. Opposite signs of these two loadings are consistent with a local source for the observed in-stream woody debris, which may leave openings in the canopy when limbs or whole trees fall to the riparian land surface or directly into streams. *F3* was interpreted as an index of channel shading. Strong negative correlations of *F3* scores with the reserved solar radiation variables—reach-mean solar insolation (R_i and R_p) and reach-maximum solar insolation ($max.R_i$ and $max.R_p$) and open-canopy angle ($max.CA_o$) (appendix 2)—were consistent with the strong positive loading from channel canopy closure.

Summarizing for the GCP sites, the most distinguishing habitat characteristics included segment-level riparian LULC and two reach-level characteristics—variability in wetted width ($cv.W_w$) and channel shading. Thus, the factor analysis of GCP data indicated that riparian LULC (with wetland as a particularly important indicator) and channel shading correspond to dominant modes of variability in riparian habitat within this study area, even as they had distinguished the GCP sites from the other four study areas in the PCA of the combined data set.

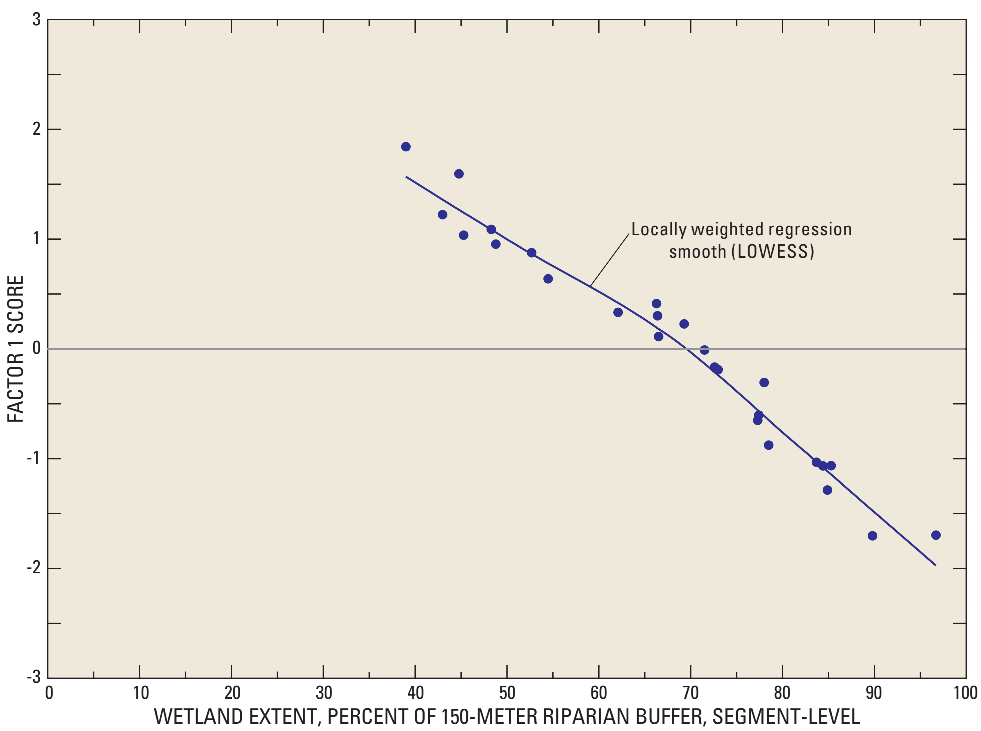

Figure 10. Relation of scores on first principal factor to segment-level wetland extent from factor analysis of data for Georgia Coastal Plain study area.

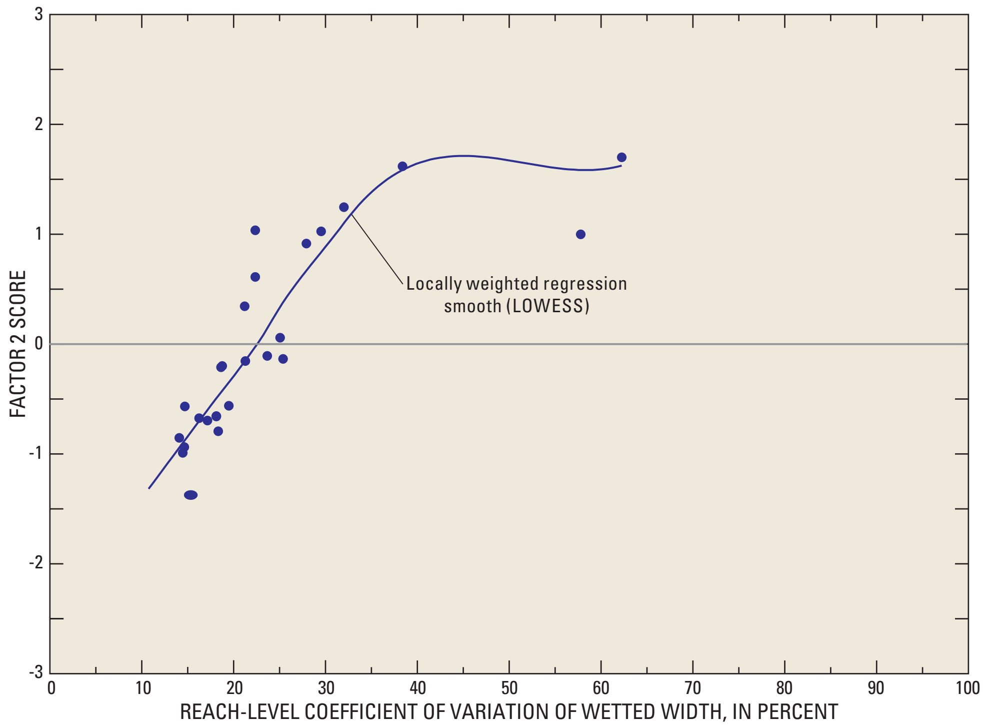

Figure 11. Relation of scores on second principal factor to reach-level variability in wetted width from factor analysis of data for Georgia Coastal Plain study area.

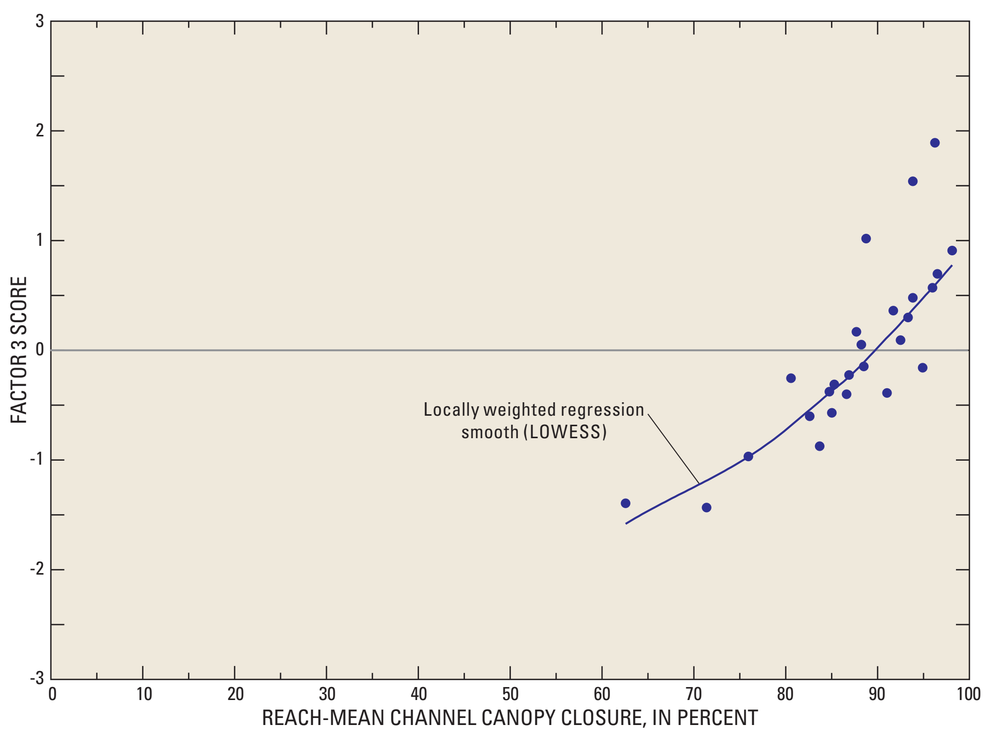

Figure 12. Relation of scores on third principal factor to reach-level channel canopy closure from factor analysis of data for Georgia Coastal Plain study area.

Riparian Characteristics Related to Nutrient Concentrations

In this section, results address the **fourth report purpose** (question D). The material is organized by chemical constituent, and rank correlations are presented for the combined multivariate data set (136 sites), and for sites within each study area. Table 11 gives results of a statistical summary of constituent concentrations by study area. In the following subsections of the report, tables of correlation results are presented for each constituent, and therein the rows corresponding to habitat variables that had no strong correlations with the constituent were omitted.

Total Nitrogen

Munn and others (in press) presented statistical comparisons of nutrient concentrations among the five study areas, and showed that CCYK and GCP had lower levels of nitrogen species than did the other three study areas. Table 4 shows that CCYK and GCP were the two study areas that averaged less than 50 percent cropland cover in studied basins, which indicates that study-unit differences in several indicators of cropland extent contributed to strong correlations of cropland extent with total nitrogen (*TN*) for all sites combined (table 12). For the combined data set, segment-level cropland extent in the riparian buffer showed increasingly positive correlations with *TN* as the riparian buffer distance increased from 50 to 250 m (*rho* increased from 0.446 to 0.581, correspondingly). Furthermore, the basin-scale indicators of cropland extent, both for the riparian buffer and the total basin, had the strongest rank correlations with *TN* ($rho \geq 0.669$ for each). The strength of this relation for the combined data set was much greater than that found by Dodds and Oakes (2008) for 57 Kansas watersheds, which also was a combined data set, but in that case representing 4 different plains ecoregions. Among the rank correlations of reach-scale habitat variables with *TN* for the combined data set, no correlation coefficients were stronger than 0.37 except that for reach-level woodland extent (Wv_{R25}; $rho = 0.491$).

Among CCYK sites, *TN* positively correlated with all basin- and segment-level indicators of riparian cropland extent (C_{S250} and C_{S150} more strongly than C_{S50} or C_{Sllt}, and segment level more strongly than basin level) (table 13). The negative correlations of *TN* with indicators of riparian woodland extent (F_{dnr} and $WwWv_{S50}$, among others) were weaker than the positive correlations with cropland. *TN* was positively correlated for CCYK sites with reach-level variables including suspended-sediment concentration (*SS*), bank vegetative cover, and stream velocity (*V* and *min.V*). These correlations may indicate that nitrogen loading from cropland was an important source of *TN* in CCYK streams, and that the predominant pathway for delivery of that loading was overland flow, as indicated by *SS*-*TN* correlation. Furthermore, the ability of aquatic biota to reduce the *TN* concentrations may have been limited by turbidity (indicated by *SS*) and nitrogen transport rates (indicated by current velocity). Compared with the correlation between *TN* and *SS*, *TN* was less strongly correlated with shading variables. This suggests a hypothesis for further study, that shading may have a less dominant role than turbidity in limiting biotic uptake of nitrogen in CCYK streams.

Few habitat variables were correlated with *TN* at CNBR sites, but among these were the indicators of basin-scale cropland extent (C_b and C_{dnr}) and the negatively correlated open-canopy angle ($max.CA_o$). The strength of the latter correlation indicates that shading may play a greater role in limiting biotic uptake of nitrogen in CNBR streams than in CCYK streams.

The importance of light availability for biotic uptake of nitrogen was evident among DLMV sites in the strong negative correlations observed between *TN* and insolation indicators—R_p and R_i (table 13). Positive correlation of *TN* with current velocity (*V*) for DLMV sites is consistent with transport rate limiting in-stream processing of nitrogen. Basin-level cropland extent (C_b and C_{dnr}) was positively related to *TN* for DLMV sites, as it was for CCYK and CNBR sites. Unique to the DLMV sites was the strong correlation of wetted width (W_w) with *TN*.

Among GCP sites, *TN* was correlated strongly only with the antecedent 60-day average water temperature (T_{w60}) (table 13). There was very little variance among GCP values of *TN*, with only three sites having *TN* concentration greater than 1.6 mg/L, so the lack of strong covariance between *TN* and other variables is not unexpected. Correlations of *TN* with the extent of both total-basin and riparian cropland were weak for sites in the GCP and WHMI study areas. For these sites, *TN* was not strongly correlated with cropland extent at any spatial scale.

Streams in the WHMI study area showed a strong positive correlation between *TN* and basin-level extent of row crops ($rho = 0.523$), and a negative correlation with reach-level frequency of undercut banks (*CvrUb*) (table 13). A possible association between soils high in organic matter (not quantified for this study) and cohesive bank materials that tend to favor undercutting may be affecting the latter correlation. Some WHMI streams drain soils that are characteristically fine to medium in granular texture, with high to moderate organic matter content (Capel and others, 2008). A negative correlation ($rho = -0.594$) between *CvrUb* and extent of riffle units (*Riff.p*) among WHMI sites further indicated that undercut banks were less common where channel materials were coarse grained and thus were noncohesive.

Table 11. Summary of water-quality and biological response variables, by study area, for sites sampled in 2003 or 2004.

[Study area codes: CCYK, Central Columbia Plateau-Yakima River Basin; CNBR, Central Nebraska; DLMV, Delmarva Peninsula; GCP, Georgia Coastal Plain; WHMI, White-Miami River Basins; d, day; deg. C, degrees Celsius; probable trophic class boundaries from Dodds and others (1998); TP, total phosphorus concentration; TN, total nitrogen concentration; mg, milligram; L, liter; m, meter; cm, centimeter; µm, micrometer; g, gram; –, not applicable; except where footnoted otherwise, the number of sites summarized was equal to the indicated number of sites]

Characteristic	Symbol	Study area code					Study area code				
		CCYK	CNBR	DLMV	GCP	WHMI	CCYK	CNBR	DLMV	GCP	WHMI
Number of sites	n_s	29	28	25	29	30	–	–	–	–	–
Water temperature, ending date of summarized period	–	08-27-2003	07-30-2003	06-15-2003	05-17-2004	08-17-2004	–	–	–	–	–
		Study area mean, unless otherwise indicated					Study area coefficient of variation, in percent				
Water temperature, daily mean, 30-d mean, deg. C	T_{w30}	[1]19.1	[2]24.5	[3]19.0	19.5	[2]20.1	14	7.3	12	3.1	5.1
Suspended sediment, mg/L	*SS*	21	158	9.6	15	12	146	93	53	45	72
Nutrients											
Total nitrogen, mg/L	*TN*	1.6	4.0	3.7	1.1	4.1	91	95	66	60	39
Probable stream trophic class, based on *TN*	–	eutrophic	eutrophic	eutrophic	mesotrophic	eutrophic	–	–	–	–	–
Dissolved nitrogen, inorganic, mg/L as N	*DIN*	1.2	2.4	3.3	0.70	3.7	113	147	76	111	45
Total phosphorus, mg/L	*TP*	.11	.72	.11	.036	.13	70	77	104	41	83
Probable stream trophic class, based on *TP*	–	eutrophic	eutrophic	eutrophic	mesotrophic	eutrophic	–	–	–	–	–
Orthophosphate, dissolved, mg/L as P	*OP*	.073	.41	.021	.004	.06	78	110	87	80	86
Biological Responses											
Chlorophyll *a*, coarse-grained benthic habitat, mg m^{-2}	*RCHL*	81	37	107	2.6	49	94	207	142	75	65
Chlorophyll *a*, fine-grained benthic habitat, mg m^{-2}	*DCHL*	47	77	20	9.8	39	93	103	140	121	51
Probable stream trophic class, based on benthic chlorophyll	–	mesotrophic	eutrophic	mesotrophic	oligotrophic	mesotrophic	–	–	–	–	–
Chlorophyll *a*, sestonic habitat, µg/L	*SCHL*	2.8	25	7.8	1.9	2.9	137	77	216	210	259
Probable stream trophic class, based on sestonic chlorophyll	–	oligotrophic	mesotrophic	oligotrophic	oligotrophic	oligotrophic	–	–	–	–	–
Ash-free dry mass (organic material), coarse-grained benthic habitat, g m^{-2}	*RAFD*	38	21	11	7.5	29	99	51	70	33	47
Ash-free dry mass (organic material), fine-grained benthic habitat, g m^{-2}	*DAFD*	103	155	109	81	113	53	43	84	73	28
Biovolume, coarse-grained benthic habitat, mm^3 cm^{-2}	*RBV*	12	3.9	.10	.29	1.3	201	188	126	126	216
Biovolume, fine-grained benthic habitat, mm^3 cm^{-2}	*DBV*	7.5	6.6	2.3	3.3	2.4	131	204	214	195	114
Macrophytes plus macroalgae, percentage cover	*AMp*	14	7.5	11	.31	1.3	136	211	165	360	147
Cell density, coarse-grained benthic habitat, 10^6 cells cm^{-2}	*RCD*	7.1	1.3	.19	.46	3.6	127	211	97	82	81
Cell density, fine-grained benthic habitat, 10^6 cells cm^{-2}	*DCD*	9.3	9.4	4.0	3.3	3.2	84	84	188	87	55

[1]Only 24 sites summarized for this variable.

[2]Only 27 sites summarized for this variable.

[3]Only 17 sites summarized for this variable.

Table 12. Correlation matrix of response variables with selected riparian and associated habitat variables, all sites combined.

[Values are Spearman's rank-correlation coefficient, *rho* (Helsel and Hirsch, 2002); **bold type** indicates strong correlation (|*rho*| >0.5); nd, not determined]

Symbol	Characteristic	Total nitrogen	Dissolved inorganic nitrogen	Total phosphorus	Dissolved ortho-phosphate	Chlorophyll *a*			Ash-free dry mass of organic material		Biovolume density		Macro-phyte and macro-algae extent	Periphyton cell density	
						Coarse-grained benthic habitat	Fine-grained benthic habitat	Seston	Coarse-grained benthic habitat	Fine-grained benthic habitat	Coarse-grained benthic habitat	Fine-grained benthic habitat		Coarse-grained benthic habitat	Fine-grained benthic habitat
Riff.p	Riffles, relative areal extent, in percent of reach	0.045	0.118	-0.025	0.150	0.366	0.289	-0.227	0.431	0.013	0.400	0.127	0.195	**0.639**	0.112
CvrWd	Extent of woody debris cover, reach level	-.046	-.033	-.208	-.290	-.456	-.287	-.221	-.419	-.008	-.297	-.214	**-.636**	-.282	-.159
$min.CC_b$	Extent of bank canopy closure, reach minimum	-.150	-.094	-.340	-.462	-.346	**-.507**	-.314	-.429	-.132	-.336	-.393	-.359	-.346	-.396
$min.CC_c$	Extent of channel canopy closure, reach minimum	-.050	.030	-.457	**-.598**	-.365	-.478	-.381	-.463	-.155	**-.530**	-.388	-.466	-.425	-.444
CC_c	Extent of channel canopy closure, reach mean	-.040	.047	-.362	-.496	-.358	-.445	-.437	-.419	-.072	-.444	-.412	**-.544**	-.331	-.471
$max.CC_c$	Extent of channel canopy closure, reach maximum	-.030	.025	-.070	-.129	-.261	-.113	-.307	-.161	.091	-.094	-.192	**-.506**	-.029	-.271
$min.CA_o$	Open canopy angle, reach minimum	-.053	-.147	.238	.359	.212	.282	.373	.380	-.001	.392	.327	**.552**	.251	.393
CA_o	Open canopy angle, reach mean	-.041	-.125	.415	**.567**	.361	.490	.403	.496	.132	**.575**	.421	**.580**	.450	.458
$max.CA_o$	Open canopy angle, reach maximum	-.059	-.133	.398	**.544**	.318	.441	.361	.422	.133	**.543**	.403	**.506**	.433	.393
$cv.CA_o$	Open canopy angle, CV of transect-level measurements, reach level	-.007	.073	-.327	-.444	-.388	-.421	-.441	-.469	-.094	-.469	-.359	**-.581**	-.358	-.430
R_p	Potential solar radiation, reach mean, as a percentage of above-canopy total	-.043	-.125	.392	**.507**	.277	.447	.431	.440	.142	.487	.398	.489	.427	**.511**
R_i	Estimated incident solar radiation, reach mean	-.039	-.135	.425	**.538**	.248	.448	.450	.424	.161	.496	.401	.460	.409	**.519**
C_b	Cropland and pasture, total-basin extent	**.669**	**.678**	.157	.159	.103	.131	-.037	.160	-.022	.020	-.130	-.047	.136	-.089
C_{dnr}	Cropland and pasture, drainage-network riparian buffer	**.669**	**.623**	.355	.417	.256	.331	.181	.385	.113	.226	.003	.067	.255	.061
C_{S250}	Cropland, 250-m buffer distance, segment mean	**.581**	**.505**	**.548**	**.505**	.172	.199	.298	.222	.143	.110	-.044	-.089	-.007	-.030
C_{S150}	Cropland, 150-m buffer distance, segment mean	**.535**	.460	**.563**	**.533**	.226	.258	.334	.271	.163	.174	-.003	-.048	.057	.029
C_{S100}	Cropland, 100-m buffer distance, segment mean	.497	.418	**.576**	**.546**	.243	.284	.357	.300	.173	.209	.022	-.019	.096	.071
C_{S50}	Cropland, 50-m buffer distance, segment mean	.446	.372	**.563**	**.521**	.272	.303	.381	.305	.176	.228	.049	.026	.121	.112
C_{Sllt}	Cropland, longitudinal linear riparian transect, segment mean	.386	.311	**.547**	**.505**	.257	.331	.385	.306	.167	.256	.076	.046	.150	.171
Ww_b	Woody wetland, total-basin extent	-.145	-.011	**-.542**	**-.753**	-.249	-.435	-.401	**-.556**	-.203	**-.629**	-.342	-.220	-.426	-.407
Ww_{dnr}	Woody wetland, drainage-network riparian buffer	-.155	-.016	**-.563**	**-.745**	-.309	-.469	-.435	**-.564**	-.210	**-.628**	-.349	-.262	-.437	-.417

Table 12. Correlation matrix of response variables with selected riparian and associated habitat variables, all sites combined.—Continued

[Values are Spearman's rank-correlation coefficient, *rho* (Helsel and Hirsch, 2002); **bold type** indicates strong correlation (|*rho*| >0.5); nd, not determined]

Symbol	Characteristic	Total nitrogen	Dissolved inorganic nitrogen	Total phosphorus	Dissolved ortho-phosphate	Chlorophyll *a*			Ash-free dry mass of organic material		Biovolume density		Macro-phyte and macro-algae extent	Periphyton cell density	
						Coarse-grained benthic habitat	Fine-grained benthic habitat	Seston	Coarse-grained benthic habitat	Fine-grained benthic habitat	Coarse-grained benthic habitat	Fine-grained benthic habitat		Coarse-grained benthic habitat	Fine-grained benthic habitat
W_{S250}	Wetland, 250-m buffer distance, segment mean	-0.219	-0.122	-0.471	**-0.579**	-0.480	-0.282	-0.377	-0.405	-.237	-0.302	-0.095	-0.356	-0.102	-0.146
W_{S150}	Wetland, 150-m buffer distance, segment mean	-.218	-.120	-.472	**-.580**	-.479	-.284	-.378	-.401	-.237	-.305	-.099	-.355	-.101	-.150
W_{S100}	Wetland, 100-m buffer distance, segment mean	-.245	-.148	-.484	**-.594**	-.471	-.282	-.377	-.405	-.233	-.303	-.104	-.354	-.097	-.146
W_{S50}	Wetland, 50-m buffer distance, segment mean	-.271	-.178	-.468	**-.586**	-.470	-.317	-.389	-.416	-.247	-.293	-.124	-.386	-.119	-.166
W_{Sllt}	Wetland, longitudinal linear riparian transect, segment mean	-.279	-.191	-.454	**-.583**	-.499	-.335	-.389	-.438	-.247	-.312	-.128	-.401	-.146	-.157
W_{R50}	Wetland land cover, 50-m buffer distance, reach mean	-.348	-.263	**-.517**	**-.602**	-.484	-.400	-.424	-.453	-.245	-.295	-.119	-.371	-.161	-.150
W_{R25}	Wetland land cover, 25-m buffer distance, reach mean	-.364	-.282	-.490	**-.590**	**-.516**	-.402	-.421	-.449	-.227	-.300	-.138	-.392	-.166	-.143
W_{Rllt}	Wetland, longitudinal linear riparian transect, reach mean	-.364	-.285	**-.503**	**-.604**	**-.525**	-.410	-.418	-.473	-.235	-.307	-.120	-.401	-.184	-.146
F_b	Forest, total-basin extent	-.373	-.279	-.475	**-.645**	-.280	-.400	-.337	-.496	-.214	-.482	-.221	-.265	-.348	-.192
F_{dnr}	Forest, drainage-network riparian buffer	-.333	-.230	**-.527**	**-.657**	-.265	-.382	-.368	-.489	-.240	-.471	-.225	-.295	-.279	-.197
Wv_{S250}	Woodland, 250-m buffer distance, segment mean	.038	.138	-.338	**-.530**	-.132	-.296	-.254	-.387	-.180	**-.507**	-.389	-.143	-.320	-.367
Wv_{R25}	Woodland, 25-m buffer distance, reach mean	.491	**.500**	.172	.144	.318	.120	.038	.079	.141	-.179	-.196	-.056	-.099	-.237
T_{w60}	Water temperature, daily mean, 60-day mean	.248	.069	**.504**	.471	.020	**.530**	**.641**	.192	.234	.223	.282	.087	.188	.378
T_{w30}	Water temperature, daily mean, 30-day mean	.120	-.075	.483	.400	-.180	.421	**.640**	.064	.215	.146	.268	-.036	.023	.365
SS	Suspended sediment concentration	.110	-.042	**.539**	.373	-.257	-.009	.416	-.070	.108	.094	-.028	-.225	-.195	-.019
TP	Total phosphorus	nd	nd	nd	nd	.090	.364	**.637**	.281	.256	.308	.109	.045	.059	.219
OP	Orthophosphate, dissolved	nd	nd	nd	nd	.291	.475	**.520**	.493	.330	.493	.188	.113	.281	.314

Table 13. Correlations of total nitrogen concentration in water samples with selected riparian and associated habitat variables, by study area.

[Study areas: CCYK, Central Columbia Plateau-Yakima River Basin; CNBR, Central Nebraska; DLMV, Delmarva Peninsula; GCP, Georgia Coastal Plain; WHMI, White-Miami River Basins; rank correlation computed as Spearman's *rho* (Helsel and Hirsch, 2002); nd, not determined; **bold** type indicates strong correlation (|*rho*| > 0.5)]

Symbol	Characteristic	Rank-correlation coefficient for indicated study area				
		CCYK	CNBR	DLMV	GCP	WHMI
W_w	Wetted width, reach mean	-0.1532	-0.0230	**0.5001**	0.2349	-0.0816
$max.W_w$	Wetted width, reach maximum	-.2638	-.0241	**.5335**	.1012	.0255
$W{:}D_w$	Width-to-depth ratio, wetted, reach mean	**-.5571**	-.0131	**.0354**	-.3573	.0148
$min.V$	Current velocity, reach minimum	**.5084**	-.0790	**-.0920**	.3910	nd
V	Current velocity, reach mean	**.5621**	-.1138	**.6554**	.1973	.0208
$CvrUb$	Extent of undercut bank cover, reach level	.2707	-.1644	**-.0670**	.2202	**-.6019**
BVC	Bank vegetative ground cover, reach mean	**.6068**	-.1397	**-.5783**	-.1919	-.1430
$max.CA_o$	Open canopy angle, reach maximum	.4387	**-.5262**	**-.3637**	-.1889	.2320
R_p	Potential solar radiation, reach mean, as a percentage of above-canopy total	.4053	-.2118	**-.5719**	-.1269	-.2206
R_i	Estimated incident solar radiation, reach mean	.4064	-.2118	**-.5622**	-.1272	-.2376
Rc_b	Row crops, total-basin extent	.1023	**.6464**	.3923	.3928	**.5227**
Rc_{dnr}	Row crops, drainage-network riparian buffer	.1174	**.5753**	**.5108**	.1303	.2682
C_b	Cropland and pasture, total-basin extent	**.5438**	**.6738**	**.6515**	.3415	.4647
C_{dnr}	Cropland and pasture, drainage-network riparian buffer	**.6076**	**.6092**	**.5346**	.1590	.2786
C_{S250}	Cropland, 250-m buffer distance, segment mean	**.8071**	-.0525	.2692	.2840	-.0613
C_{S150}	Cropland, 150-m buffer distance, segment mean	**.7461**	-.1078	.1138	.0853	-.1609
C_{S100}	Cropland, 100-m buffer distance, segment mean	**.6966**	-.1193	-.0585	.0615	-.1730
C_{S50}	Cropland, 50-m buffer distance, segment mean	**.7051**	-.1429	-.1962	.1962	-.2255
C_{Sllt}	Cropland, longitudinal linear riparian transect, segment mean	**.6727**	-.1959	-.2718	.0614	-.2234
Ww_b	Woody wetland, total-basin extent	**-.5182**	-.2131	-.1558	-.1487	.1468
Ww_{dnr}	Woody wetland, drainage-network riparian buffer	**-.6487**	-.0367	.0423	.0762	.0235
F_b	Forest, total-basin extent	**-.5036**	-.1875	-.4985	-.2656	-.4357
F_{dnr}	Forest, drainage-network riparian buffer	**-.5423**	-.3142	-.3038	-.0899	-.2326
Wv_{S250}	Woodland, 250-m buffer distance, segment mean	**-.5039**	.1697	-.4985	.0338	.1505
Wv_{S150}	Woodland, 150-m buffer distance, segment mean	**-.5064**	.2025	-.3285	.1036	.2764
Wv_{S100}	Woodland, 100-m buffer distance, segment mean	**-.5596**	.2173	-.1269	.0338	.3421
Wv_{S50}	Woodland, 50-m buffer distance, segment mean	**-.5892**	.2507	.2762	.0312	.4132
Wv_{Sllt}	Woodland, longitudinal linear riparian transect, segment mean	**-.5822**	.3153	.2497	-.0100	.3957
Wv_SL_{llt}	Woodland patch length, longitudinal linear riparian transect, segment mean	**-.5846**	.1949	.0077	-.0922	.4455
$WwWv_b$	Forest plus woody wetland, total-basin extent	**-.5247**	-.1795	**-.6269**	-.2950	-.4505
$WwWv_{dnr}$	Forest plus woody wetland, drainage-network riparian buffer	**-.5750**	-.3016	-.4562	-.1856	-.2348
$WwWv_{S250}$	Combined wetland and woodland, 250-m buffer distance, segment mean	**-.5034**	.1697	**-.5162**	-.1966	.1719
$WwWv_{S150}$	Combined wetland and woodland, 150-m buffer distance, segment mean	**-.5064**	.2025	-.3300	-.0250	.2354
$WwWv_{S100}$	Combined wetland and woodland, 100-m buffer distance, segment mean	**-.5596**	.2173	-.1262	.0052	.2556
$WwWv_{S50}$	Combined wetland and woodland, 50-m buffer distance, segment mean	**-.5892**	.2507	.2269	-.0608	.2271
$WwWv_{Sllt}$	Combined wetland and woodland, longitudinal linear riparian transect, segment mean	**-.5822**	.3153	.2289	.0462	.2430
T_{w60}	Water temperature, daily mean, 60-day mean	-.0313	-.0171	-.3701	**.5063**	-.1292
SS	Suspended sediment concentration	**.7298**	-.2556	-.3094	-.1047	-.2114

Dissolved Inorganic Nitrogen

Among the individual LULC variables, those most strongly correlated with *DIN* were basin-scale cropland extent variables (*rho* ≥ 0.623) for all sites combined. There was a monotonic, scale-dependent increase in the correlation strength between *DIN* and cropland extent in the riparian zone as habitat scale increased from reach to basin and as buffer width increased from 25 to 250 m (table 12; fig. 4).

For CCYK sites, the strongest positive correlations with *DIN* were those with segment-level extent of riparian cropland and with suspended sediment (*SS*) concentration (*rho* ≥ 0.669 for each; table 14). Correlations of *DIN* with cropland extent for CCYK sites were strongest for the riparian buffer distances greater than 100 m, but correlation strength was weaker at the basin scale. *DIN*-cropland correlations were much weaker at the reach scale for all study areas. For CNBR and DLMV sites, *DIN* was strongly correlated with total-basin cropland extent (C_b). In contrast with CCYK sites, *DIN* was more strongly correlated with cropland extent for the total basin (C_b) than with riparian cropland (C_{dnr}) for the other study areas (table 14). In contrast with CCYK sites, the segment-level correlations of *DIN* with cropland extent were weak for the other study areas.

Strong negative correlations of both riparian and total-basin woodland extent with *DIN* were consistent at basin and segment levels for CCYK sites. Other notably strong relations with *DIN* among CCYK sites were the negative correlations with riparian woody wetland extent, Ww_{dnr} (*rho* = -0.692), width-to-depth ratio ($W{:}D_w$) , and the positive correlations with reach-mean velocity (*V*) and *Froude* (table 14).

When sites lacking segment-level wetlands (W_{S50}) were excluded, the negative correlation of riparian wetland extent with *DIN* among 49 sites was strong at the reach and segment levels, but not at the basin level where the LULC class tested was woody wetlands (Ww_{dnr}). These results are indicative of the role played by riparian wetland vegetation in removing dissolved nutrients from soil water and shallow ground water passing through riparian zones (Lowrance and others, 1984; Peterjohn and Correll, 1984; Gregory and others, 1991). The effectiveness of riparian wetland in reducing nitrogen concentrations in surface water also has been well documented (Fisher and Acreman, 2004; Scott and others, 2007); however, the correlation results in this study (tables 12, 13, and 14) did not consistently confirm this capacity of wetlands for the sampled streams in agricultural areas.

For DLMV streams only, *DIN* had strong negative correlations with indicators of insolation and water temperature (R_p, R_i, T_{w60}, and T_{w30}) (table 14). The positive correlations of hydraulic width (W_w) and velocity (*V*) with *DIN* among DLMV and GCP sites also were not found in the other study areas. Plant growth and uptake of inorganic nitrogen could be indicated by negative correlations of insolation and water temperature with *DIN*, and an uptake effect on *DIN* would be consistent with a downstream trend of decreasing periphyton and macrophyte abundances in larger reaches because of discharge-associated effects—such as scouring of the streambed. An inverse relation of *DIN* to the extent of pool habitat for GCP sites corresponded to a significantly larger median concentration of *DIN* (rank-sum $W = 55$, $p = 0.0021$) at sites with less than 25-percent coverage by pool habitat (median of 0.76 mg/L) than at the remaining eight GCP sites (median of 0.25 mg/L). These findings are consistent with slower transport rates promoting greater nitrogen uptake. Although the spatial extent of riparian wetland was not correlated with *DIN*, stream interaction with woody wetland has been reported elsewhere to play a role (Scott and others, 2007) and probably is greater where velocities in the channel are slower.

Among WHMI sites, the frequency of undercut banks (*CvrUb*) was correlated strongly, though negatively, with *DIN*. As previously suggested, the negative *CvrUb* correlation with nitrogen concentrations may reflect a possible association between soils high in organic matter and the presence of cohesive bank materials that tend to allow bank undercutting. Organic soils in riparian zones present ideal conditions for denitrification of incoming agricultural runoff (Lowrance and others, 1984).

Phosphorus Species

Among the individual study areas, correlations between phosphorus concentrations and riparian habitat variables were rarely strong for more than one study area. This lack of more widely applicable relations was particularly apparent for the dissolved phosphorus species examined, and only a non-riparian physical property (suspended sediment) was correlated with total phosphorus for multiple study areas.

Table 14. Correlations of dissolved inorganic nitrogen concentration in water samples with selected riparian and associated habitat variables, by study area.

[Study areas: CCYK, Central Columbia Plateau-Yakima River Basin; CNBR, Central Nebraska; DLMV, Delmarva Peninsula; GCP, Georgia Coastal Plain; WHMI, White-Miami River Basins; rank correlation computed as Spearman's *rho* (Helsel and Hirsch, 2002); nd, not determined; **bold** type indicates strong correlation (|*rho*| > 0.5)]

Symbol	Characteristic	Rank-correlation coefficient for indicated study area				
		CCYK	CNBR	DLMV	GCP	WHMI
$min.W_w$	Wetted width, reach minimum	-0.1752	-0.0090	0.3992	**0.6656**	-0.2237
W_w	Wetted width, reach mean	-.2476	-.0279	**.5266**	**.6226**	-.0733
$max.W_w$	Wetted width, reach maximum	-.3331	-.0203	**.5612**	**.5061**	.0460
$cv.W_w$	Wetted width, CV of transect-level measurements, reach level	-.3988	.0597	-.0862	**-.5945**	.1067
$W{:}D_w$	Width-to-depth ratio, wetted, reach mean	**-.6008**	.0085	.1131	.0619	.0126
$min.V$	Current velocity, reach minimum	.4570	-.1275	-.0879	**.6546**	nd
V	Current velocity, reach mean	**.5737**	-.1620	**.6538**	**.5241**	.0531
Froude	Froude number, reach mean	**.5170**	-.1730	.4608	.4827	.0565
Pool.p	Pools, relative areal extent, reach level	-.3106	-.0759	nd	**-.5791**	.0496
CvrUb	Extent of undercut bank cover, reach level	.1295	-.2658	-.0441	.3125	**-.6213**
BVC	Bank vegetative ground cover, reach mean	**.5759**	-.1219	**-.5791**	-.1833	-.1145
$max.CA_o$	Open canopy angle, reach maximum	.3950	**-.5256**	-.3746	-.1555	.2652
R_p	Potential solar radiation, reach mean, as a percentage of above-canopy total	.2752	-.2003	**-.5865**	-.0626	-.1949
R_i	Estimated incident solar radiation, reach mean	.2862	-.2003	**-.5778**	-.0616	-.2113
Rc_b	Row crops, total-basin extent	.0612	**.6497**	.3838	.3675	**.5090**
Rc_{dnr}	Row crops, drainage-network riparian buffer	.0921	**.5578**	**.5062**	.1932	.2655
C_b	Cropland and pasture, total-basin extent	.4897	**.6710**	**.6400**	.4462	.4439
C_{dnr}	Cropland and pasture, drainage-network riparian buffer	**.5263**	**.5928**	.4931	.2643	.2863
C_{S250}	Cropland, 250-m buffer distance, segment mean	**.7672**	-.0898	.2015	.3470	.0016
C_{S150}	Cropland, 150-m buffer distance, segment mean	**.7167**	-.1253	.0277	.1038	-.0958
C_{S100}	Cropland, 100-m buffer distance, segment mean	**.6690**	-.1396	-.1323	.0343	-.1155
C_{S50}	Cropland, 50-m buffer distance, segment mean	**.6780**	-.1741	-.2269	.1883	-.1746
C_{Sllt}	Cropland, longitudinal linear riparian transect, segment mean	**.6243**	-.2146	-.2988	.1413	-.1763
Ww_b	Woody wetland, total-basin extent	**-.5738**	-.1868	-.1804	.1795	.1339
Ww_{dnr}	Woody wetland, drainage-network riparian buffer	**-.6924**	.0656	.0162	.3819	.0112
F_b	Forest, total-basin extent	**-.5049**	-.1486	-.4500	-.3915	-.4160
F_{dnr}	Forest, drainage-network riparian buffer	**-.5399**	-.2107	-.2269	-.4161	-.2370
Wv_{S50}	Woodland, 50-m buffer distance, segment mean	**-.5528**	.3300	.3346	-.0236	.3875
Wv_{Sllt}	Woodland, longitudinal linear riparian transect, segment mean	**-.5389**	.3607	.3304	.0577	.3689
Wv_SL_{llt}	Woodland patch length, longitudinal linear riparian transect, segment mean	**-.5851**	.2315	.0769	-.0211	.4264
$WwWv_b$	Forest plus woody wetland, total-basin extent,	**-.5418**	-.1396	**-.5885**	-.3887	-.4324
$WwWv_{dnr}$	Forest plus woody wetland, drainage-network riparian buffer,	**-.5861**	-.1987	-.3708	-.2773	-.2458
$WwWv_{S50}$	Combined wetland and woodland, 50-m buffer distance, segment mean	**-.5528**	.3300	.2546	.0318	.1790
$WwWv_{Sllt}$	Combined wetland and woodland, longitudinal linear riparian transect, segment mean	**-.5389**	.3607	.2697	-.0502	.1992
T_{w60}	Water temperature, daily mean, 60-day mean	-.1853	-.1838	**-.5637**	.3491	-.1623
T_{w30}	Water temperature, daily mean, 30-day mean	-.1844	-.1099	**-.5515**	.2027	-.2054
SS	Suspended sediment concentration	**.7066**	-.3651	-.4107	-.3065	-.2111

Total Phosphorus

Munn and others (in press) reported that total phosphorus (*TP*) ranged from 0.004 to 2.69 mg/L, with sites in CNBR having a significantly greater mean concentration (0.72 mg/L) and the GCP sites having a significantly lower mean concentration (0.036 mg/L) than sites in the other study areas. *TP* concentrations in the CCYK, WHMI, and DLMV study areas were similar (table 11).

For all sites combined, *TP* was strongly correlated with segment-level cropland extent and suspended sediment concentration (*SS*). The positive correlations with riparian cropland extent and *SS* (table 12) underscore the importance of agriculture and conservation practices for reducing near-stream sources of phosphorus. The weakness of the relation between *TP* and total-basin extent of cropland (C_b) may be explained by the cumulative effect of several factors: the inefficiency of sediment delivery to channels, channel storage of sediment and phosphorus, and improved phosphorus management on cropland. Another process that may link sediment with *TP* in positive correlations is light-limiting turbidity that could block in-stream uptake of phosphorus by aquatic vegetation.

For the combined data set, there also were strong negative correlations of *TP* with reach- and basin-level extent of riparian wetland, and with basin-level extent of forest (table 12). The reach-level negative correlations with *TP* for wetland indicators W_{R50} and W_{Rllt} point to the importance of extended contact of stream water with overbank areas (Scott and others, 2007) where sediment-borne phosphorus may settle into storage, and phosphorus may be taken up into plant biomass (Fisher and Acreman, 2004). The strong negative correlations between *TP* and riparian woodland extent at the basin level (Ww_{dnr} and F_{dnr}) may similarly reflect uptake by woodland, the capacity to filter runoff from adjacent uplands, and the storage of phosphorus bound to overbank flood deposits and contained in buried vegetal debris (Lowrance and others, 1984).

Among CCYK sites, the strongest correlations of total phosphorus were with suspended sediment (*SS*), segment- and reach-level extent of riparian cropland, and basin-level extent of row crops (table 15). Among the riparian variables, cropland extent within the 250-m buffer area (C_{S250}) was the most strongly correlated with *TP*. A beneficial effect of riparian woodland on *TP* at CCYK sites may have been indicated by the negative correlation with woodland patch length ($Wv_S L_{llt}$) at the segment level (table 15). In the arid West, water stresses limit riparian woodland development (Minshall, 1978); however, the runoff-filtering effect may be achieved by long, narrow woodland patches that do not necessarily dominate areally within the stream-buffer polygons analyzed for this study.

None of the habitat variables were strongly correlated with *TP* at the CNBR sites. Concentrations of suspended sediment (*SS*) were relatively high at most CNBR sites, indicating that in-stream processing of phosphorus may have been little affected by riparian-habitat conditions.

Suspended sediment (*SS*) was strongly correlated with *TP* for three of the study areas, and there also was variability among study areas in the slope of this relation (fig. 13). Among DLMV sites, *TP* was most strongly correlated with antecedent water temperature (T_{w30}, T_{w60}) and *SS*, whereas for GCP sites light availability (R_i, R_p) was most strongly correlated with *TP* (table 15). *SS* and channel canopy closure ($min.CC_c$, CC_c) also were correlated with *TP* among the GCP sites. The strong correlations of *TP* with *SS*, channel shading, and light availability indicate that in GCP streams *TP* tends to be lowest where in-stream processing of nutrients is enhanced by available insolation and water clarity.

Orthophosphate

As was the case for *TP*, concentrations of dissolved orthophosphate (*OP*) generally were much higher for CNBR streams than for the other study areas (table 11). High concentrations of OP in eastern Nebraska streams and elsewhere in that region have been documented previously (Omernik, 1977; Helgesen and others, 1994).

For all sites combined, strong correlations were found between *OP* and segment-level extent of cropland (all variables) and reach-level indicators of insolation (R_p, R_i) and shading (table 12), including channel canopy ($min.CC_c$, CA_o). Negative correlations with *OP* also were noted for basin- and reach-level wetland extent in riparian buffers, such as for Ww_{dnr} (*rho* = -0.745) and W_{Rllt} (*rho* = -0.604). In contrast, for woodland extent in riparian buffers, negative correlations with *OP* were limited to wide buffers at the segment or basin scales (F_{dnr}, Wv_{S250}), where the LULC signal often includes upland as well as riparian vegetation.

For CCYK streams, antecedent water temperature (T_{w30}, T_{w60}) was negatively correlated with *OP* (table 16), possibly indicative that aquatic plant uptake of phosphorus was more effective when water was warmer. Uptake by benthic algae was suggested also by results for CNBR sites, where width-to-depth ratio (W:D_w) was a strong negative correlate of *OP*, and Duff and others (2008) reported process measurements for nitrogen uptake at one of the CNBR sites that are consistent with this hypothesis. Negative correlations of *OP* with light availability (R_i, R_p) and woodland extent in the total basin (F_b) were strong only for GCP sites. The strong correlations of light availability with *OP* for GCP sites indicate that shading may be a factor limiting the biological uptake of nutrients.

Table 15. Correlations of total phosphorus concentration in water samples with selected riparian and associated habitat variables, by study area.

[Study areas: CCYK, Central Columbia Plateau-Yakima River Basin; CNBR, Central Nebraska; DLMV, Delmarva Peninsula; GCP, Georgia Coastal Plain; WHMI, White-Miami River Basins; rank correlation computed as Spearman's *rho* (Helsel and Hirsch, 2002); nd, not determined; **bold** type indicates strong correlation (|*rho*| > 0.5)]

Symbol	Characteristic	Rank-correlation coefficient for indicated study area				
		CCYK	CNBR	DLMV	GCP	WHMI
$min.CC_c$	Extent of channel canopy closure, reach minimum	0.1233	-0.0129	-0.2302	**0.5742**	-0.0483
CC_c	Extent of channel canopy closure, reach mean	.2615	.1999	-.1800	**.5192**	-.0974
CA_o	Open canopy angle, reach mean	-.2143	-.3306	.4541	**-.5000**	.1078
$max.CA_o$	Open canopy angle, reach maximum	-.1842	-.3117	**.5348**	-.4124	-.0227
R_p	Potential solar radiation, reach mean, as a percentage of above-canopy total	-.1867	-.2748	.3400	**-.6005**	.2129
R_i	Estimated incident solar radiation, reach mean	-.1544	-.2748	.3326	**-.6073**	.2233
Rc_b	Row crops, total-basin extent	**-.6620**	.0898	-.0615	.0660	-.2173
Rc_{dnr}	Row crops, drainage-network riparian buffer	**-.6313**	.0624	-.1108	-.0893	-.1998
C_{S250}	Cropland, 250-m buffer distance, segment mean	**.7166**	-.0279	.0700	-.3402	-.0471
C_{S150}	Cropland, 150-m buffer distance, segment mean	**.6771**	-.0547	.1377	**-.5019**	.0131
C_{S100}	Cropland, 100-m buffer distance, segment mean	**.7114**	-.0591	.1531	-.3323	.0296
C_{S50}	Cropland, 50-m buffer distance, segment mean	**.7129**	-.0766	.0592	-.2644	.0695
C_{Sllt}	Cropland, longitudinal linear riparian transect, segment mean	**.7037**	-.1544	.0656	-.3610	.0936
C_{R50}	Cropland land cover, 50-m buffer distance, reach mean	**.5100**	.1432	-.3903	-.2801	-.0834
C_{R25}	Cropland land cover, 25-m buffer distance, reach mean	**.5280**	-.0109	-.1505	nd	-.0435
C_{Rllt}	Cropland land cover, longitudinal linear riparian transect, reach mean	**.5317**	-.0327	-.1136	nd	-.0169
Wv_SL_{llt}	Woodland patch length, longitudinal linear riparian transect, segment mean	**-.5498**	.0115	-.0762	.0836	-.2277
T_{w60}	Water temperature, daily mean, 60-day mean	-.4861	.0006	**.7549**	-.0575	.3962
T_{w30}	Water temperature, daily mean, 30-day mean	-.4843	.0873	**.7672**	.0544	.4915
SS	Suspended sediment concentration	**.7276**	.3005	**.6345**	**.5942**	-.2821

Table 16. Correlations of dissolved orthophosphate concentration in water samples with selected riparian and associated habitat variables, by study area.

[Study areas: CCYK, Central Columbia Plateau-Yakima River Basin; CNBR, Central Nebraska; DLMV, Delmarva Peninsula; GCP, Georgia Coastal Plain; WHMI, White-Miami River Basins; rank correlation computed as Spearman's *rho* (Helsel and Hirsch, 2002); nd, not determined; **bold** type indicates strong correlation (|*rho*| > 0.5)]

Symbol	Characteristic	Rank-correlation coefficient for indicated study area				
		CCYK	CNBR	DLMV	GCP	WHMI
$W{:}D_w$	Width-to-depth ratio, wetted, reach mean	-0.0215	**-0.5480**	-0.1501	0.2870	0.0868
$CvrOv$	Extent of overhanging vegetation cover, reach level	.0250	**.5307**	.1590	-.0392	.1292
R_p	Potential solar radiation, reach mean, as a percentage of above-canopy total	-.2453	-.1325	-.1795	**-.5415**	.0583
R_i	Estimated incident solar radiation, reach mean	-.2122	-.1325	-.1833	**-.5477**	.0695
Rc_b	Row crops, total-basin extent	**-.5592**	-.0250	.3433	.4992	-.1130
Rc_{dnr}	Row crops, drainage-network riparian buffer	**-.5606**	-.0330	-.0058	.3884	-.1831
F_b	Forest, total-basin extent	.3236	.2876	-.3729	**-.5379**	-.1793
Wv_SL_{llt}	Woodland patch length, longitudinal linear riparian transect, segment mean	**-.5101**	-.1404	.3383	.1178	-.1530
T_{w60}	Water temperature, daily mean, 60-day mean	**-.5889**	-.1439	.2661	.0183	.2839
T_{w30}	Water temperature, daily mean, 30-day mean	**-.5901**	-.1138	.2808	.0024	.3728

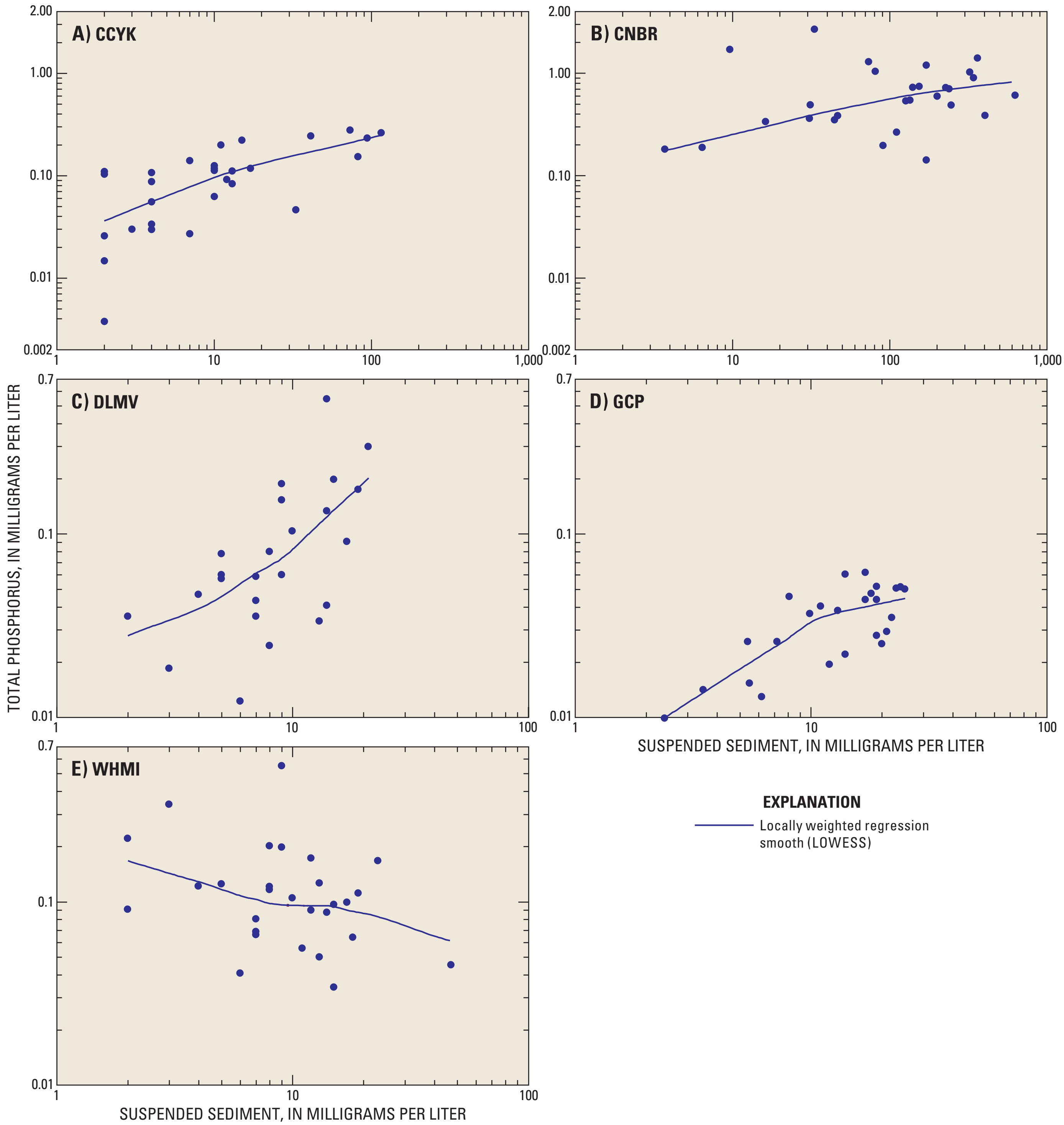

Figure 13. Relation of total phosphorus to suspended-sediment concentration for (*A*) Central Columbia Plateau-Yakima River Basin (CCYK), (*B*) Central Nebraska (CNBR), (*C*) Delmarva Peninsula (DLMV), (*D*) Georgia Coastal Plain (GCP), and (*E*) White-Miami River Basins (WHMI) study areas.

Review of Nutrients Relations to Riparian Conditions

For all sites combined, nutrient concentrations were correlated with the extent of riparian cropland. In particular, segment-level extent of cropland within the 250-m riparian buffer was correlated strongly with all four of the examined nutrient species. The relations of nutrient concentrations to riparian conditions also can be summarized by reviewing which riparian habitat variables were strongly correlated with each nutrient species for more than one study area (table 17).

The only riparian variable strongly correlated with total nitrogen concentration for more than two study areas was basin-level extent of riparian cropland in the buffer area (C_{dnr}) for the CCYK, CNBR, and DLMV study areas. For two study areas, riparian woodland extent ($WwWv_{S250}$) was negatively correlated with *TN* (table 13), consistent with the use of woodland buffers as a conservation practice intended to reduce nutrient loadings to streams. Another conservation treatment, vegetative ground cover on streambanks (*BVC*), also was strongly correlated with both *TN* and *DIN* for two study areas, but the signs of the correlations were unexpectedly positive for CCYK streams whereas they were negative for all other study areas. For dissolved inorganic nitrogen, only reach-mean current velocity (*V*) and basin-level extent of riparian cropland (C_{dnr} or Rc_{dnr}) were its strong correlates in three study areas. In addition, bank vegetative cover (*BVC*) and one non-riparian stream-habitat variable (wetted width) were correlated strongly with *DIN* in two study areas.

Overall for *TN* and *DIN*, riparian characteristics correlated with both nitrogen species among multiple study areas were basin-level extents of cropland (C_{dnr}) and *BVC*. The correlations with these riparian variables underscore the importance of agricultural management practices for reducing nitrogen delivery from near-stream sources. Among the considered stream-habitat characteristics, only reach-mean current velocity (*V*) was correlated strongly with both nitrogen species among multiple study areas. The positive sign of all strong correlations of nitrogen concentrations with current velocity or *Froude* indicates that the rate of nitrogen transport may be a factor affecting in-stream nitrogen uptake by benthic vegetation.

For all sites combined, both phosphorus species were positively correlated with segment-level riparian cropland and negatively correlated with riparian woody wetland and forest at the basin scale and riparian wetland at the reach scale. Among the study-unit relations with phosphorus concentrations, the only variable correlated strongly with *TP* for three study areas was a non-riparian characteristic (*SS*), and *OP* was not correlated strongly with any variable in multiple study areas. Concentrations of suspended sediment and of phosphorus were relatively high at most CNBR sites, where none of the measured habitat variables were strongly correlated with *TP*. In GCP streams, the negative correlations of *TP* and *OP* with light availability indicate that concentrations tend to be lowest where in-stream processing of phosphorus is enhanced by available insolation. At CCYK sites, both *TP* and *OP* were negatively correlated with riparian woodland patch length (Wv_SL_{llt}) at the segment level, possibly indicating that the length of woodland patches may be more important than areal dominance for effective filtering of phosphorus from runoff.

Although there were no habitat variables with strong correlations with orthophosphate for more than one study area, in the CCYK and GCP study areas the correlations of habitat variables (water temperature and insolation, respectively) with concentrations of *OP* were consistent with the expectation that autotrophic production in streams would be a factor affecting *OP* concentrations in many study streams. This same pair of negatively correlated habitat variables was noted for *DIN* at DLMV streams.

Overall for phosphorus species, the only reach-level riparian habitat characteristics correlated with both phosphorus species at even one study area each were insolation and antecedent water temperature. This may indicate that light-limitation of in-stream processing of phosphorus may be the most common riparian control on phosphorus concentrations.

Retention.—Streams retain nutrients, particularly inorganic nitrogen, through microbial uptake in benthic habitats, but the uptake capacity is affected by bed sediment properties (porosity and hydraulic conductivity), water residence time, delivered nutrient loads (especially nitrogen), and the processing potential of the biotic community (Duff and others, 2008). Although nutrients may be removed as water moves through the streambed, nutrients in the water column are commonly transported effectively where contact with the streambed is limited. However, channel structural elements (such as woody debris) can trap transported material and slow the current to create areas favorable for particle deposition; moreover, where these features slow the current they retard the transport of dissolved nutrients as well, increasing the potential for their biotic uptake (Gregory and others, 1991). As examples, swifter current velocities (*V*) for many of the CCYK, DLMV, and GCP sites may limit in-stream uptake of *DIN* by reducing the residence time within such reaches. Swifter velocities could result from channel modifications associated with agriculture or other development, including channelization or snag removal. Relative to the subject of this report (riparian habitat), the importance of structure-related retention processes lies in the typically close linkage between channel complexity and adjacent riparian-zone structure and composition.

Table 17. Summary of correlations of response variables with riparian and associated habitat characteristics.

[Rank-correlation strength measured using Spearman's *rho*; strong rank correlations satisfy the inequality (|*rho*| > 0.5); na, correlation not analyzed. **Response variables:** *TN*, total nitrogen concentration in water samples; *DIN*, dissolved inorganic nitrogen concentration in water samples; *TP*, total phosphorus concentration in water samples; *OP*, dissolved orthophosphate concentration in water samples; *RCHL* and *DCHL*, chlorophyll *a* concentrations in samples from coarse-grained and fine-grained benthic habitats, respectively; *SCHL*, chlorophyll *a* concentration in water samples; *RAFD* and *DAFD*, organic material density as measured by ash-free dry mass of samples from coarse-grained and fine-grained benthic habitats, respectively; *RBV* and *DBV*, algal biovolume in samples from coarse-grained and fine-grained benthic habitats, respectively; and *AMp*, reach-mean areal extent of aquatic macrophytes and macroalgae]

Habitat characteristic	Habitat variable symbol(s) (tables 4–5)	Number of study areas with strong correlation(s) with indicated response variable												Total number of strong correlations with nutrient species for study areas	Total number of strong correlations with biological responses for study areas
		TN	*DIN*	*TP*	*OP*	*RCHL*	*DCHL*	*SCHL*	*RAFD*	*DAFD*	*RBV*	*DBV*	*AMp*		
Wetted width	W_w	1	2	0	0	0	1	0	0	0	0	0	0	3	1
Bankfull width	W_{bf}	0	0	0	0	0	0	0	0	0	0	1	1	0	2
Current velocity or Froude number	V or *Froude*	2	3	0	0	1	1	1	1	0	1	0	0	5	5
Extent of pool or riffle units	*Pool.p* or *Riff.p*	0	1	0	0	0	1	0	1	0	0	0	0	1	2
Bank vegetative cover extent	*BVC*	2	2	0	0	0	1	1	0	1	0	1	1	4	5
Overhanging vegetation extent	*CvrOv*	0	0	0	1	0	0	1	0	0	0	0	0	1	1
Woody debris extent	*CvrWd*	0	0	0	0	0	1	0	0	0	0	1	1	0	3
Bank canopy closure	CC_b	0	0	0	0	0	1	1	0	0	0	0	1	0	3
Channel canopy closure	CC_c	0	0	1	0	0	1	0	0	0	0	0	2	1	3
Open canopy angle	CA_o	0	0	1	0	0	1	0	0	0	0	0	2	1	3
Insolation exposure	R_p, R_i	1	1	1	1	0	1	1	1	0	0	1	2	4	6
Cropland extent, riparian, basin level	C_{dnr} or Rc_{dnr}	3	3	1	1	0	0	0	0	0	0	0	0	8	0
Cropland extent, segment level	C_{S100}, C_{S50}, or C_{Sllt}	1	1	1	0	0	1	1	0	0	0	1	1	4	4
Cropland extent, reach level	C_{R50}, C_{R25}, or C_{Rllt}	0	0	1	0	0	0	0	0	0	0	1	1	1	2

Table 17. Summary of correlations of response variables with riparian and associated habitat characteristics—Continued.

[Rank-correlation strength measured using Spearman's *rho*; strong rank correlations satisfy the inequality (|*rho*| > 0.5); na, correlation not analyzed. **Response variables:** *TN*, total nitrogen concentration in water samples; *DIN*, dissolved inorganic nitrogen concentration in water samples; *TP*, total phosphorus concentration in water samples; *OP*, dissolved orthophosphate concentration in water samples; *RCHL* and *DCHL*, chlorophyll *a* concentrations in samples from coarse-grained and fine-grained benthic habitats, respectively; *SCHL*, chlorophyll *a* concentration in water samples; *RAFD* and *DAFD*, organic material density as measured by ash-free dry mass of samples from coarse-grained and fine-grained benthic habitats, respectively; *RBV* and *DBV*, algal biovolume in samples from coarse-grained and fine-grained benthic habitats, respectively; and *AMp*, reach-mean areal extent of aquatic macrophytes and macroalgae]

Habitat characteristic	Habitat variable symbol(s) (tables 4–5)	Number of study areas with strong correlation(s) with indicated response variable												Total number of strong correlations with nutrient species for study areas	Total number of strong correlations with biological responses for study areas
		TN	*DIN*	*TP*	*OP*	*RCHL*	*DCHL*	*SCHL*	*RAFD*	*DAFD*	*RBV*	*DBV*	*AMp*		
Woody wetland extent, riparian, basin level	Ww_{dnr}	1	1	0	0	1	0	0	0	0	0	0	0	2	1
Wetland extent, segment level	W_{S100}, W_{S50}, or W_{Sllt}	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wetland extent, reach level	W_{R50}, W_{R25}, or W_{Rllt}	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Woodland extent, riparian, basin level	F_{dnr}, $WwWv_{dnr}$	1	1	0	0	0	0	0	0	0	0	0	1	2	1
Woodland extent, segment level	Wv_{S100}, Wv_{S50}, or Wv_{Sllt}	1	1	0	0	0	1	1	1	0	0	1	1	2	5
Woodland extent, reach level	Wv_{R50}, Wv_{R25}, or Wv_{Rllt}	0	0	0	0	0	0	0	0	0	0	1	1	0	2
Water temperature	T_{w30} or T_{w60}	1	1	1	1	0	1	2	1	0	0	0	0	4	4
Suspended sediment	*SS*	1	1	3	0	0	0	1	0	0	0	1	1	5	3
Total nitrogen	*TN*	na	na	na	na	0	0	0	0	0	0	0	0	na	0
Dissolved inorganic nitrogen	*DIN*	na	na	na	na	0	1	1	0	1	0	0	0	na	3
Total phosphorus	*TP*	na	na	na	na	0	1	1	0	0	0	0	0	na	2
Dissolved orthophosphate	*OP*	na	na	na	na	0	0	0	0	0	0	0	0	na	0

For example, the canopy condition of many of the stream sites may have contributed to a high photosynthetic demand for nitrogen. Correlations of nitrogen concentrations with canopy or insolation variables were strong for CNBR and DLMV sites. For sites in the DLMV, the strong positive correlation of *TN* with wetted width may indicate a decreasing capacity for nitrogen retention within larger stream reaches farther down the river (Vannote and others, 1980). Alternatively, it may reflect a difference in hydrologic pathways wherein focused recharge of agricultural runoff and shallow subsurface flow paths promote substantial nitrogen influx to streams through seepage interfaces (Peterjohn and Correll, 1984; Capel and others, 2008; Duff and others, 2008). In another example, the inverse relation of riparian wetland extent with *DIN* for CCYK sites was consistent with the role of riparian wetland in reducing nitrogen loads in surface runoff through retention and biogeochemical transformation (Fisher and Acreman, 2004; Scott and others, 2007). However, this inverse relation might also reflect less nitrogen loading to streams from decreased cropland extent in riparian areas where woody wetland is prominent. Beyond these examples of possible nitrogen retention, the strong negative correlation between antecedent water temperature and *OP* for CCYK sites was consistent with the importance of autotrophic activity to increase phosphorus retention in western, open-canopy streams (Minshall, 1978).

Summary.—Across all nutrient species, basin-level extent of cropland in the riparian buffer, bank vegetative ground cover, insolation exposure, and segment-level extent of riparian cropland correlated most strongly with nutrient concentrations. Each of these habitat characteristics was correlated strongly with concentrations of a nutrient species in four or more study-area-level instances (table 17). Taking *BVC* as an example, *TN* was correlated with *BVC* in two study areas and *DIN* was correlated with *BVC* in two study areas, summing to a total of four instances where a strong correlation was found at the study-area level. Associated in-stream habitat characteristics that were correlated with nutrient concentrations in four or more study-area instances were suspended sediment concentration, current velocity, and antecedent water temperature.

Riparian Characteristics Related to Biological Responses

In this report, sensitivity of a specific biological response to riparian characteristics was evaluated on the basis of rank correlations with riparian characteristics, including scale-specific indicators of LULC. This section of the report addresses the **fifth report purpose** (question E). For each biological response variable group, results for the combined set of sites are presented first, followed by the relations that were specific to the individual study areas. (In the tables of correlation results presented for each biological response, rows corresponding to habitat variables that had no strong correlations with the biological response were omitted.)

Chlorophyll in Benthic Habitats

Among all sites combined, chlorophyll *a* concentrations in samples from fine-grained benthic habitat (*DCHL*) were strongly correlated only with antecedent water temperature (T_{w60}) and bank shading ($min.CC_b$) (table 12). Concentrations of chlorophyll *a* in periphyton samples from coarse-grained benthic habitat (*RCHL*) (either rock or wood) for the combined data set were strongly correlated only with reach-level riparian wetland extent (table 12). Sites in the GCP study area had both the most extensive riparian wetlands and shading and the smallest concentrations of *DCHL* and *RCHL* (table 11); therefore, GCP sites accounted for much of the variance reflected in these correlations. In the CNBR study area, where *DCHL* levels also were highest, antecedent water temperature was the warmest.

Concentrations of chlorophyll *a* in periphyton samples from rock or wood substrate (*RCHL*) were not correlated strongly with any of the examined variables for CCYK, CNBR, DLMV, and WHMI sites (table 18). For CCYK sites, *DCHL* was strongly correlated with wetted width (table 19; fig. 14*A*). CCYK streams, on average, had the most open-canopy conditions, and under such conditions, periphyton growth would tend to be enhanced where greater wetted width equates with more potentially habitable substrate. In contrast, for CNBR sites *DCHL* was negatively correlated with mean water depth, probably indicative of its effect in generally turbid streams to reduce light penetration to benthic algae.

Among GCP sites, *RCHL* was negatively correlated with reach-mean current velocity (*V*) (fig. 15) and woody wetland extent in the basin-scale riparian network (Ww_{dnr}; table 18). In view that *V* was strongly correlated with mean wetted width ($rho = 0.731$) for GCP sites, it appears that chlorophyll *a* concentrations in GCP samples from coarse wood substrate tended to be larger at narrow reaches where flows were slower, as opposed to wider streams where velocities generally were faster.

Only among DLMV sites was *DCHL* strongly correlated with nutrient concentrations, but the nature of these associations was mixed. DLMV was the only study area that demonstrated the expected positive association between *DCHL* and *TP* (Munn and others, in press). *TP* concentrations may be indicative of its local nonpoint sources. Dissolved inorganic nitrogen concentrations were negatively correlated with *DCHL* among DLMV sites, where correlations of *DCHL* with light availability and segment-level riparian cropland extent were stronger than those with nutrient concentrations (table 19).

Table 18. Correlations of chlorophyll *a* concentration in coarse-grained benthic habitat with selected riparian and associated habitat variables, by study area.

[Study areas: CCYK, Central Columbia Plateau-Yakima River Basin; CNBR, Central Nebraska; DLMV, Delmarva Peninsula; GCP, Georgia Coastal Plain; WHMI, White-Miami River Basins; rank correlation computed as Spearman's *rho* (Helsel and Hirsch, 2002); nd, not determined; **bold** type indicates strong correlation (|*rho*| > 0.5)]

Symbol	Characteristic	Rank-correlation coefficient for indicated study area				
		CCYK	CNBR	DLMV	GCP	WHMI
$cv.W_w$	Wetted width, coefficient of variation of transect-level measurements, reach level	0.1241	-0.0996	-0.2269	**0.5136**	0.2118
V	Current velocity, reach mean	-.0030	-.3848	.0762	**-.5584**	.2551
Froude	Froude number, reach mean	-.0358	-.1793	.0536	**-.5002**	.2505
Ww_{dnr}	Woody wetland, drainage-network riparian buffer	-.0815	.2212	-.2762	**-.5283**	-.0961

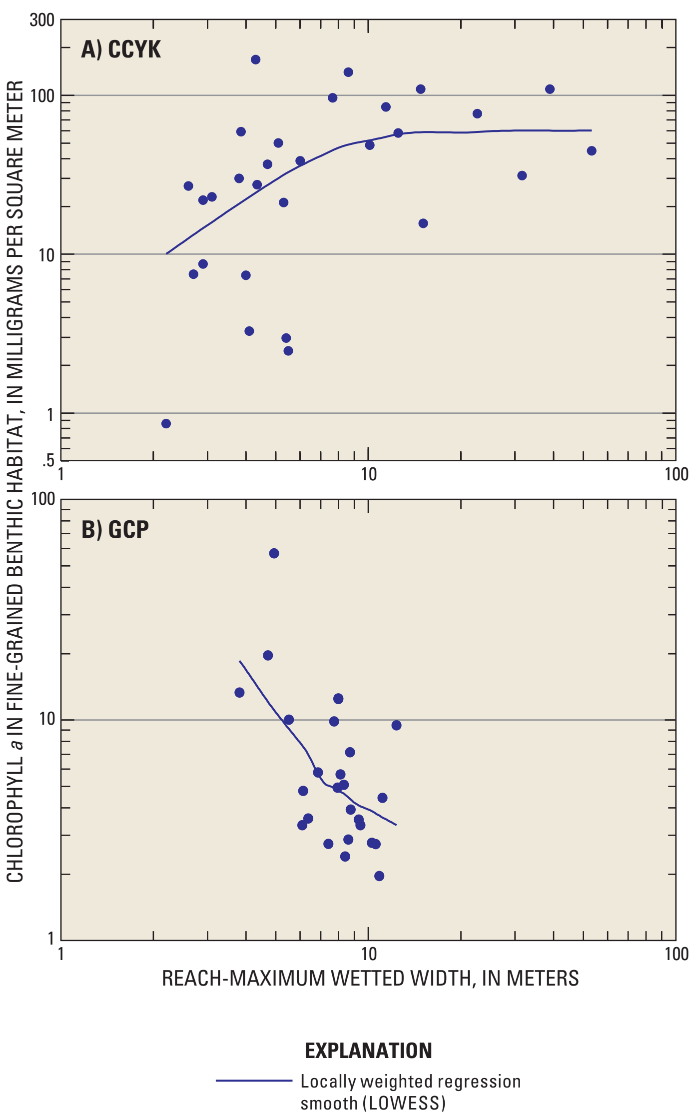

Figure 14. Relations of chlorophyll *a* in fine-grained benthic habitat to reach-maximum wetted width, for (*A*) Central Columbia Plateau-Yakima River Basin (CCYK) sites and (*B*) Georgia Coastal Plain (GCP) sites.

DLMV reaches were dominated geomorphologically by runs, and bed substrate was predominantly sand (mean frequency = 50 percent of sample points) or silt-clay (mean frequency = 36 percent of sample points). Duff and others (2008) reported that their DLMV study site had bed sediment that was high in organic matter. That study also measured an abundant potential for denitrification in the organic-rich bed sediment of the DLMV site, but a relatively shallow depth of stream-water penetration into the bed limited the actual denitrification (Duff and others, 2008). Collectively, the results at DLMV sites may be indicative that nitrogen uptake by aquatic macrophytes, plus substrate conditions that enhance the effectiveness of denitrification of the stream water, are affecting the *DIN* concentrations more than *DCHL* does.

Among GCP sites, the sole strong correlation with *DCHL* was for reach-maximum wetted width ($max.W_w$) (table 19; fig. 14*B*). In the Georgia Coastal Plain and elsewhere, channel shading limits benthic algal growth in most small streams (Munn and others, in press). However, the correlation between wetted width and channel shading was too weak (*rho* = -0.450 for CC_c with $max.W_w$) to conclude that the negative correlation indicated in figure 14*B* was related to channel shading. Instead, $max.W_w$ was strongly correlated (*rho* = 0.618) with mean current velocity, indicating hydraulic scouring as a possible control on *DCHL*. Among WHMI sites, levels of *DCHL* did not associate strongly with any of the studied riparian or in-stream characteristics.

Chlorophyll in Seston

Study-unit mean concentrations of chlorophyll *a* in seston (*SCHL*) varied by more than a factor of 10, ranging from 1.9 µg/L for GCP sites to 25 µg/L for CNBR sites (table 11). Table 11 also indicates that of the various criteria for trophic class of streams, for *SCHL* alone none of the study-unit mean concentrations was classified as a eutrophic condition. Similarly, Munn and others (in press) reported that fewer sites were classified as eutrophic on the basis of *SCHL* measurements than were so classified using the other criteria proposed by Dodds and others (1998).

Table 19. Correlations of chlorophyll *a* concentration in fine-grained benthic habitat with selected riparian and associated habitat variables, by study area.

[Study areas: CCYK, Central Columbia Plateau-Yakima River Basin; CNBR, Central Nebraska; DLMV, Delmarva Peninsula; GCP, Georgia Coastal Plain; WHMI, White-Miami River Basins; rank correlation computed as Spearman's *rho* (Helsel and Hirsch, 2002); nd, not determined; **bold** type indicates strong correlation (|*rho*| > 0.5); CV, coefficient of variable]

Symbol	Characteristic	Rank-correlation coefficient for indicated study area				
		CCYK	CNBR	DLMV	GCP	WHMI
W_w	Wetted width, reach mean	**0.5463**	-0.0940	-0.1639	-0.4866	-0.0104
$max.W_w$	Wetted width, reach maximum	**.5180**	-.1200	-.1816	**-.5321**	.0621
D_w	Water depth, reach mean	.0927	**-.5220**	.0418	-.2887	-.2834
Froude	Froude number, reach mean	-.2141	.2072	**-.5410**	-.3211	.0778
CvrWd	Extent of woody debris cover, reach level	.2363	-.1177	**-.6688**	.3741	-.0060
BVC	Bank vegetative ground cover, reach mean	-.2415	-.0260	**.7341**	.4150	.2780
$min.CC_b$	Extent of bank canopy closure, reach minimum	-.0831	-.2285	**-.6820**	-.0086	-.1541
CC_b	Extent of bank canopy closure, reach mean	-.0283	-.3292	**-.7600**	-.3077	-.2034
$min.CC_c$	Extent of channel canopy closure, reach minimum	-.1469	.1331	**-.6432**	.0780	-.1441
CC_c	Extent of channel canopy closure, reach mean	-.1500	-.0934	**-.6687**	.1518	-.1784
CA_o	Open canopy angle, reach mean	-.1108	.1710	**.6277**	.0650	.1959
$cv.CA_o$	Open canopy angle, CV of transect-level measurements, reach level	.0576	-.0079	**-.7598**	-.0306	-.1390
R_p	Potential solar radiation, reach mean, as a percentage of above-canopy total	.0542	.0605	**.7113**	-.1829	-.0525
R_i	Estimated incident solar radiation, reach mean	.0192	.0605	**.7035**	-.1763	-.0296
C_{S100}	Cropland, 100-m buffer distance, segment mean	-.4803	.1125	**.6957**	.1570	.0411
C_{S50}	Cropland, 50-m buffer distance, segment mean	-.4632	.0920	**.7391**	.0969	.0071
C_{Sllt}	Cropland, longitudinal linear riparian transect, segment mean	-.4037	.1378	**.7039**	.0902	.0340
Wv_{S100}	Woodland, 100-m buffer distance, segment mean	.4340	-.1132	**-.6400**	.3211	-.1199
Wv_{S50}	Woodland, 50-m buffer distance, segment mean	.4427	-.1350	**-.7626**	.2199	-.1790
Wv_{Sllt}	Woodland, longitudinal linear riparian transect, segment mean	.4432	-.2068	**-.7506**	.0597	-.0865
Wv_SL_{llt}	Woodland patch length, longitudinal linear riparian transect, segment mean	.3577	-.0667	**-.6113**	-.0580	-.1658
Wv_SFg_{llt}	Woodland gap frequency, longitudinal linear riparian transect, segment mean	.1680	.0318	**.6043**	.1703	.3032
Wv_RFg_{llt}	Woodland gap frequency, longitudinal linear riparian transect, reach mean	-.2700	.0058	**.5545**	.0650	.1785
$WwWv_{S100}$	Woodland, 100-m buffer distance, segment mean	.4340	-.1132	**-.6339**	-.3617	-.0958
$WwWv_{S50}$	Woodland, 50-m buffer distance, segment mean	.4427	-.1350	**-.7217**	-.4256	-.0969
$WwWv_{Sllt}$	Combined wetland and woodland, longitudinal linear riparian transect, segment mean	.4432	-.2068	**-.7315**	-.4360	-.1138
T_{w60}	Water temperature, daily mean, 60-day mean	.2965	-.1115	**.6863**	.0243	-.0023
T_{w30}	Water temperature, daily mean, 30-day mean	.2730	-.1869	**.6618**	-.0154	.0438
DIN	Dissolved nitrogen, inorganic	-.3089	-.1897	**-.5383**	-.2599	.1773
TP	Total phosphorus concentration	-.4542	-.4564	**.5348**	-.1344	.1297

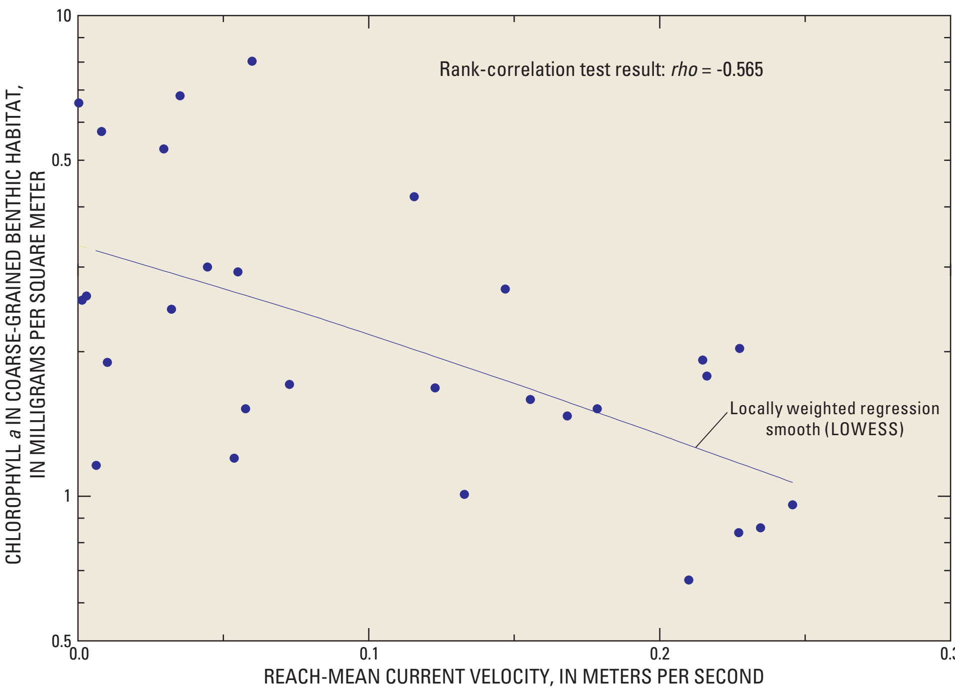

Figure 15. Relation of chlorophyll *a* in coarse-grained benthic habitat to reach-mean velocity for Georgia Coastal Plain sites.

Strong correlations with sestonic chlorophyll concentrations for all sites combined were limited to antecedent water temperature and concentrations of phosphorus species (table 12). Values for both of these variables differed markedly among study areas; for example, the GCP sites had the smallest mean concentrations of both *SCHL* and *TP*, and the CNBR means for both variables were the highest (table 11). However, the strong correlation with total phosphorus was probably attributable, in part, to the presence of phosphorus within the algae in the seston (Munn and others, in press). Antecedent water temperatures also differed among study areas, but the two variables in this category also were strongly correlated with *SCHL* within the study-unit data sets for CCYK and DLMV sites. These two study areas also had the coolest stream water, on average (table 11). Temperature may control algal biomass under certain conditions, but also may simply reflect natural differences among study areas (Munn and others, in press).

Several examples of multiple linear regression models were examined to see whether nutrient concentrations plus antecedent water temperature, channel shading, water depth, *Froude*, or width-to-depth ratio could combine to explain the *SCHL* levels at the sites in the combined data set. Model selection was guided by comparison of multiple statistical indexes of explainable variance, precision, information content, and efficiency, including R^2, residual standard error, Mallow's *Cp*, and the PRESS statistic (Ott and Longnecker, 2001, p. 714-716) . The best multiple regression model explained 65.5 percent of the variance in *SCHL* using two nutrient species (*TP* and *DIN*) plus antecedent water temperature (T_{w30}). Because of missing values, the model was fit using 118 sites. The ordinary least-squares estimate of the linear model is given here,

$$\log_{10} SCHL = 0.315 + 0.288 \cdot z\left(\log_{10} TP\right) + 0.383 \cdot z\left(T_{w30}\right) - 0.107 \cdot z\left(DIN^{0.25}\right), \qquad (3)$$

where

- TP is total phosphorus concentration, in milligrams per liter;
- T_{w30} is antecedent 30-day mean water temperature in degrees Celsius;
- DIN is dissolved inorganic nitrogen concentration, in milligrams per liter; and
- $\log_{10}$ is the base-10 logarithm of the indicated variables.

Following scale transformation of variables (to improve univariate normality), the independent variables were transformed to their standard-normal scores (*z*-scores) to equalize their weight (and thus equalize the scale of coefficients) for the regression modeling. The function, *z*, in equation 3 indicates this standardization of the independent variables. Test results for the regression model coefficients and other regression statistics are included in appendix 3. All four coefficients in equation 3 were significant ($|t| > 2.6$, $p \leq 0.0103$. The regression model coefficients indicate that water temperature was the most important explanatory variable, followed by *TP*, and finally *DIN*. *SCHL* was greater where water temperature was warmer and *TP* concentration was larger, just as their individual correlations had indicated. But, with other variables held constant, *SCHL* was greater where *DIN* was less, possibly indicating a feedback (nitrogen uptake) by the response variable affecting one of the "independent" variables. However, this uptake effect only was about one-third as important as water temperature in the regression model, as indicated by the small size of the coefficient for *DIN*.

These results indicate that *SCHL* may be useful as one sentinel of nutrient enrichment for generally small, agricultural streams as examined in this study. But the authors view these results as inconclusive because much unexplained variance in *SCHL* remains, and other studies indicate that some of the explained variance likely resulted from the nutrient content of the sestonic algae themselves. Furthermore, some authors have argued previously that sestonic algae are not actively functioning as the algal base component of the ecosystem unless they are phytoplanktonic, which also implies that a functional sestonic community is restricted to larger, deeper rivers (Cushing and Allan, 2001).

Among CCYK sites, the only strong negative correlation of *SCHL* was with stream gradient (S_w) (table 20). The inverse association of *SCHL* with stream gradient among CCYK sites may indicate a tendency for more sestonic algae in reaches with open canopies and deeper water. The 16 CCYK reaches with stream gradient not greater than 6 m/km had significantly deeper mean water depth (rank-sum test, $p=0.0028$), less extensive riffle habitat (rank-sum test, $p=0.041$), and less channel shading (CC_c, rank-sum test, $p=0.024$) than did the 13 sites with steeper gradients. A typically open channel canopy (median of zero for CC_c) may explain the greater concentrations of sestonic chlorophyll at these CCYK sites.

Within the DLMV study area, antecedent water temperature, insolation, bank vegetative ground cover (*BVC*), suspended sediment (*SS*), *TP*, and segment-level extent of riparian cropland were positively correlated with *SCHL* (table 20). Negatively correlated with *SCHL* at DLMV sites were the riparian extent of woodland at the segment level, riparian canopy closure, *DIN*, and *Froude* (which distinguishes the tranquility or rapidity of the flow [Dingman, 1984]). Rapid transport of both nutrients and sestonic algae would allow less time for sestonic production of chlorophyll in these small streams. However, the positive relations of *SCHL* with *SS*, *TP*, and riparian cropland may indicate that nutrient loadings or factors enhancing nutrient and sediment delivery to streams also may have a major effect on *SCHL* in DLMV streams.

SCHL was negatively correlated to channel shading ($max.CC_c$) among CNBR sites and was positively correlated with insolation (R_i, R_p) for DLMV sites. Of the habitat characteristics strongly correlated with *SCHL* among all sites or within multiple study areas, only the shading/insolation indicators of channel openness were direct measures of riparian effects.

Organic Material

Concentrations of organic material, as measured by ash-free dry mass per unit area, correlated strongly with periphyton cell density for samples from rock or wood substrate ($rho=0.572$). For the combined data set, organic material in samples from coarse-grained benthic habitats (*RAFD*) correlated strongly with basin-level extent of woody wetland (Ww_b and Ww_{dnr}; table 12). In the section, "Study-Unit Summaries and Comparisons," woody wetland was most common in the DLMV and GCP study areas (table 4). Furthermore, *RAFD* was not correlated strongly with nutrient concentrations, nor any other habitat characteristic examined. Moreover, organic material in samples from fine-grained benthic habitats (*DAFD*) was not strongly correlated with any of the variables examined for this report when all sites were considered together.

Neither *RAFD* nor *DAFD* was correlated strongly with nutrient concentrations among either CCYK or CNBR sites. Potential insolation (R_p) was positively correlated with *RAFD* for CCYK sites (table 21), and ground-covering bank vegetation (*BVC*) was correlated negatively with *DAFD* for those sites (table 22).

Among CNBR sites, none of the studied habitat variables were correlated strongly with *DAFD*, but antecedent water temperature (T_{w60}), day of the year (t_J), and current velocity (*V*) were each negatively correlated with *RAFD* (table 21). High ambient temperatures during the 2003 sampling period in central Nebraska explain the similarity of relations with water temperature and day of the year. During this heat wave, at one central Nebraska weather station for example, daily maximum air temperature averaged 32°C and reached at least 30°C on 22 days of the 29-day period that ended with the end of sampling, while less than 0.3 mm of rainfall fell during that period (National Climatic Data Center, 2003). Because of these conditions, active irrigation of cropland in the CNBR study basins was widespread (J.D. Frankforter, U.S. Geological Survey, oral commun., 2007); therefore, a number of the small study streams likely were receiving bank seepage and (or) irrigation tailwater runoff that progressively increased streamflow during the sampling period. Discharge increases (ungaged for most sampled streams) may have resulted in hydraulic scouring of some targeted woody snag samples or increased turbidity that limited photosynthesis by periphyton.

Among DLMV sites, there were no strong correlates of *RAFD*. Within fine-grained benthic habitats at DLMV sites, *DAFD* was strongly correlated only with the frequency of riparian woodland gaps (Wv_RFg_{llt}) at the reach scale (table 22). Bankfull width (W_{bf}) also was strongly correlated with riparian woodland gap frequency ($rho=0.550$) and inversely so with riparian woodland-extent indicators, such as $WwWv_{S50}$, $WwWv_{Sllt}$, and *CvrWd* ($rho<$ -0.5 for each).

Table 20. Correlations of chlorophyll *a* concentration in seston with selected riparian and associated habitat variables, by study area.

[Study areas: CCYK, Central Columbia Plateau-Yakima River Basin; CNBR, Central Nebraska; DLMV, Delmarva Peninsula; GCP, Georgia Coastal Plain; WHMI, White-Miami River Basins; rank correlation computed as Spearman's *rho* (Helsel and Hirsch, 2002); nd, not determined; **bold** type indicates strong correlation (|*rho*| > 0.5)]

Symbol	Characteristic	Rank-correlation coefficient for indicated study area				
		CCYK	CNBR	DLMV	GCP	WHMI
S_w	Gradient, reach mean	**-0.5693**	0.0003	-0.2029	0.1352	-0.0245
Froude	Froude number, reach mean	.1648	.1647	**-.5293**	-.2700	-.2804
CvrOv	Extent of overhanging vegetation cover, reach level	.0926	-.2018	.3392	**-.5498**	-.1698
BVC	Bank vegetative ground cover, reach mean	.2639	.0619	**.6034**	-.3368	.0570
CC_b	Extent of bank canopy closure, reach mean	.1473	-.0454	**-.5754**	.0892	-.0341
$max.CC_c$	Extent of channel canopy closure, reach maximum	-.3582	-.4729	-.2879	-.0566	.0859
$cv.CA_o$	Open canopy angle, coefficient of variation of transect-level measurements, reach level	-.3688	-.2841	**-.6107**	.2649	-.1941
R_p	Potential solar radiation, reach mean, as a percentage of above-canopy total	.3944	.4132	**.6215**	-.1620	.0430
R_i	Estimated incident solar radiation, reach mean	.3399	.4132	**.6167**	-.1616	.0493
C_{S50}	Cropland, 50-m buffer distance, segment mean	-.0068	.2135	**.5111**	-.2648	-.0430
C_{Sllt}	Cropland, longitudinal linear riparian transect, segment mean	.0297	.2704	**.5619**	-.3433	.0071
Wv_{S50}	Woodlands, 50-m buffer distance, segment mean	-.1094	-.3175	**-.6767**	-.0054	-.1744
Wv_{Sllt}	Woodlands, longitudinal linear riparian transect, segment mean	-.1591	-.2627	**-.6897**	-.0877	-.1413
Wv_SL_{llt}	Woodlands patch length, longitudinal linear riparian transect, segment mean	-.0631	.0099	**-.5601**	-.1079	-.2494
Wv_SFg_{llt}	Woodlands gap frequency, longitudinal linear riparian transect, segment mean	-.0273	-.3158	**.5052**	-.1354	.3603
$WwWv_{S50}$	Combined wetland and woodland, 50-m buffer distance, segment mean	-.1094	-.3175	**-.6283**	.1450	.1410
$WwWv_{Sllt}$	Combined wetland and woodland, longitudinal linear riparian transect, segment mean	-.1591	-.2627	**-.6710**	.2627	.0753
T_{w60}	Water temperature, daily mean, 60-day mean	**.5696**	.2790	**.7954**	-.1185	.2593
T_{w30}	Water temperature, daily mean, 30-day mean	**.5609**	.2656	**.7846**	-.0423	.2432
SS	Suspended sediment concentration	.0185	.1095	**.5774**	.3871	-.1687
DIN	Dissolved nitrogen, inorganic, concentration	.0675	-.3525	**-.5744**	-.2539	-.3980
TP	Total phosphorus concentration	-.1067	-.1018	**.5645**	.4310	.4782

These DLMV results are consistent with the hypothesized relation of *DAFD* to Wv_RFg_{llt} as a surrogate for two riparian characteristics associated with riparian woodland gaps—greater canopy openness to insolation (*rho* = 0.506 for correlation of Wv_RFg_{llt} with $min.CA_o$) and a LULC shift from woodland to cropland (*rho* = 0.632 for correlation of Wv_RFg_{llt} with C_{S50}).

Among GCP sites, concentrations of dissolved inorganic nitrogen (*DIN*) were strongly correlated with *DAFD* (table 22). Scott and others (2007) showed inverse relations between riparian extent of woody wetland and two inorganic nitrogen species, and attributed these relations to biochemical transformation and retention of ammonia and nitrate in these frequently flooded riparian areas. Thus, for the GCP sites, where *DIN* and *DAFD* concentrations were small relative to those of the other study areas, the effects of woody wetland margins along most streams probably suppressed the concentrations of *DIN* and *DAFD* both by physical shading and biochemical retention.

Table 21. Correlations of ash-free dry mass of organic material in coarse-grained benthic habitat with selected riparian and associated habitat variables, by study area.

[Study areas: CCYK, Central Columbia Plateau-Yakima River Basin; CNBR, Central Nebraska; DLMV, Delmarva Peninsula; GCP, Georgia Coastal Plain; WHMI, White-Miami River Basins; rank correlation computed as Spearman's *rho* (Helsel and Hirsch, 2002); nd, not determined; **bold** type indicates strong correlation (|*rho*| > 0.5)]

Symbol	Characteristic	Rank-correlation coefficient for indicated study area				
		CCYK	CNBR	DLMV	GCP	WHMI
t_J	Day of the year	0.2039	**-0.5711**	0.2615	0.0508	-0.0225
V	Current velocity, reach mean	-.1296	**-.5100**	-.2286	.2320	.4727
$Pool.p$	Pools, relative areal extent	-.1501	.1215	nd	.0098	**-.5371**
R_p	Potential solar radiation, reach mean, as a percentage of above-canopy total	**.5225**	-.1066	.1314	-.1044	-.0857
Wv_{S100}	Woodland, 100-m buffer distance, segment mean	-.1852	.0821	-.1351	**-.5014**	.1136
T_{w60}	Water temperature, daily mean, 60-day mean	-.1374	**-.5422**	-.3511	-.1342	-.3162

Table 22. Correlations of ash-free dry mass of organic material in fine-grained benthic habitat with selected riparian and associated habitat variables, by study area.

[Study areas: CCYK, Central Columbia Plateau-Yakima River Basin; CNBR, Central Nebraska; DLMV, Delmarva Peninsula; GCP, Georgia Coastal Plain; WHMI, White-Miami River Basins; rank correlation computed as Spearman's *rho* (Helsel and Hirsch, 2002); nd, not determined; **bold** type indicates strong correlation (|*rho*| > 0.5)]

Symbol	Characteristic	Rank-correlation coefficient for indicated study area				
		CCYK	CNBR	DLMV	GCP	WHMI
BVC	Bank vegetative ground cover, reach mean	**-0.5181**	0.1057	0.2120	0.0263	0.2518
Wv_RFg_{llt}	Woodland gap frequency, longitudinal linear riparian transect, reach mean	-0.0508	0.3443	**0.5247**	0.1856	0.0716
DIN	Dissolved nitrogen, inorganic, concentration	-0.3165	-0.1166	-0.1354	**0.5446**	-0.0153

Algal Biovolume

Overall correlations with biovolume density in periphyton samples from coarse-grained benthic habitat (*RBV*) were strongest for basin-level woody wetland extent (both in the total basin and in the drainage-network riparian buffer), channel canopy closure ($min.CC_c$), and open-canopy angle (table 12). The negative correlation of *RBV* with segment-level riparian woodland extent in the 250-m buffer also was strong for the combined sites, but appeared to be more indicative of basin-level land-cover differences than a general riparian effect: the strength of this correlation for buffers narrower than 100 m was weak ($|rho| < 0.3$) . Biovolume density in samples from fine-grained benthic habitat (*DBV*) was not correlated strongly with any examined variables when analyzed for all sites combined.

There were strong correlations of biovolume density in rock or wood samples (*RBV*) with three of the habitat variables for the GCP sites (table 23). Those negative correlations with reach-minimum wetted width ($min.W_w$) and with current velocity ($min.V$ and V) indicate that periphyton biovolume was responding to similar habitat factors as did *RCHL*. Swifter currents may have limited biovolume density on woody snags through hydraulic scouring. For DLMV sites, *RBV* was negatively correlated with variability of open-canopy angles ($cv.CA_o$) within the study reaches. Because the weaker correlations with indicators of insolation and canopy openness were all positive relations, the negative correlation with $cv.CA_o$ was not interpreted as evidence for an inverse relation with light availability. One possible reason that so few correlations with biovolume were found for coarse-grained benthic samples could be that another unmeasured limiting factor, such as a toxic chemical(s), is the dominant control on biovolume. For example, Kosinski (1984) reported that pesticides had altered algal biomass in agricultural streams.

The expectation from previous findings (Dodds and others, 2002; Porter and others, 2008) was that *DBV* would be positively correlated with nitrogen concentrations and the extent of cropland. A positive correlation with segment-level riparian cropland was found for DLMV sites. Among CCYK sites, *DBV* was correlated strongly only with reach-level riparian extent of cropland (table 24); however, *DBV*

Table 23. Correlations of biovolume density in coarse-grained benthic habitat with selected riparian and associated habitat variables, by study area.

[Study areas: CCYK, Central Columbia Plateau-Yakima River Basin; CNBR, Central Nebraska; DLMV, Delmarva Peninsula; GCP, Georgia Coastal Plain; WHMI, White-Miami River Basins; rank correlation computed as Spearman's *rho* (Helsel and Hirsch, 2002); nd, not determined; **bold** type indicates strong correlation (|*rho*| > 0.5)]

Symbol	Characteristic	Rank-correlation coefficient for indicated study area				
		CCYK	CNBR	DLMV	GCP	WHMI
$min.W_w$	Wetted width, reach minimum	0.1136	-0.0447	0.0332	**-0.5569**	0.2040
$min.V$	Current velocity, reach minimum	.2185	.0346	-.4089	**-.5335**	nd
V	Current velocity, reach mean	.1399	-.1374	-.4308	**-.5166**	.2895
$cv.CA_o$	Open canopy angle, coefficient of variation of transect-level measurements, reach level	.0089	-.1067	**-.5108**	-.3004	.0991

decreased with increasing cropland extent. *DBV* at CCYK sites was not strongly correlated with suspended sediment concentration (*SS*). *SS* was the only strong negative correlate of *DBV* among CNBR sites, but width-to-depth ratio ($W{:}D_w$) was positively correlated with biovolume. Because low $W{:}D_w$ ratios in sediment-laden water would tend to limit photosynthesis at the streambed, either burial by sediment or light limitation may be factors affecting *DBV* levels at CNBR sites. In a large, national data set, Porter and others (2008) also found a negative correlation between algal biovolume and *SS*.

Among DLMV sites, *DBV* was negatively correlated with segment- and reach-level woodland extent within riparian buffers of up to 50 m, with channel shading ($max.CC_c$ and $cv.CA_o$), and with frequency of woody debris (table 24). Strong positive correlations with *DBV* among DLMV sites included those with segment-level riparian extent of cropland (C_{SIlt} and C_{S50}), insolation and canopy openness (R_i, R_p, and $min.CA_o$), channel width (W_{bf}), and frequency of riparian woodland gaps. Thus, cropland proximity and light availability appear to be the dominant underlying factors affecting algal biovolume in fine-grained depositional benthic habitats of the DLMV study reaches. In considering why these results were limited to the DLMV sites, three points are germane. For the GCP, the sort of negative relation between cropland and woodland that dominates DLMV riparian areas does not exist because of the dominance of riparian wetland and nearly complete absence of cropland within 50 m of streams; and GCP streams were almost uniformly well shaded, so there was little chance for a strong correlation with light availability. Second, the CCYK and CNBR sites have far less riparian woodland and wetted channels generally were not shaded, so it was not surprising that algal-habitat relations in those study areas differed from those in the DLMV. Third, the WHMI sites have riparian LULC more similar to the DLMV, although the typical balance between cropland and woodland is shifted somewhat in the Corn Belt as compared to the DLMV (tables 4 and 5), particularly within the 50 m closest to the stream. Nevertheless, the lack of a strong correlation between either cropland extent or light availability and algal biovolume in the WHMI indicates that some nonriparian, physical habitat property, perhaps substrate coarseness, is behind the difference in algal-habitat relations between the WHMI and DLMV study areas.

Aquatic Macrophytes and Macroalgae

For all sites combined, the reach-mean areal extent of aquatic macrophytes and macroalgae (*AMp*) was most strongly correlated with light availability and channel shading, as indicted respectively by open-canopy angle (CA_o) and canopy closure (CC_c) (table 12). Relations with other riparian-associated habitat metrics such as woody debris frequency (*CvrWd*) were negatively correlated with *AMp*. These results were consistent with light being the primary resource in the conceptual model of plant growth in streams (Biggs, 1996).

Among CCYK sites, negative correlations of *AMp* were strongest with basin-level woodland extent variables that included riparian woodland extent along the full drainage network (F_{dnr}) (table 25). An inverse relation between *AMp* and F_{dnr} extent indicated that nutrient filtering or uptake in the riparian woodland buffer (possibly in concert with channel shading) might have limited macrophyte or macroalgae growth at CCYK sites. Weak correlations between *AMp* and channel shading indicators indicate that it was some factor other than shading that was driving the woodland-related effect.

Among CNBR sites, *AMp* was correlated most strongly with canopy openness ($cv.CA_o$ and CA_o) and insolation (R_i and R_p). Strong negative correlations with canopy closure (CC_c) suggest that channel shading limited macroalgae growth (table 25). *AMp* in CNBR streams also was inversely related to segment-level cropland extent, but there were two patterns noted that indicate that the limiting effect may have been related to increased flows from irrigated cropland rather than

Table 24. Correlations of biovolume density in fine-grained benthic habitat with selected riparian and associated habitat variables, by study area.

[Study areas: CCYK, Central Columbia Plateau-Yakima River Basin; CNBR, Central Nebraska; DLMV, Delmarva Peninsula; GCP, Georgia Coastal Plain; WHMI, White-Miami River Basins; rank correlation computed as Spearman's *rho* (Helsel and Hirsch, 2002); nd, not determined; **bold** type indicates strong correlation (|*rho*| > 0.5)]

Symbol		Rank-correlation coefficient for indicated study area				
		CCYK	CNBR	DLMV	GCP	WHMI
$W{:}D_w$	Width-to-depth ratio, wetted, reach mean	0.3690	**0.6621**	0.1531	-0.3292	0.3005
W_{bf}	Bankfull width, reach mean	.1557	.0312	**.5609**	-.2684	-.1002
CvrWd	Extent of woody debris cover, reach level	.0735	-.1140	**-.5568**	.2526	-.0334
BVC	Bank vegetative ground cover, reach mean	.0601	-.0507	**.5452**	.1864	.0887
$max.CC_c$	Extent of channel canopy closure, reach maximum	-.2451	-.1314	**-.5543**	.0400	.2575
$min.CA_o$	Open canopy angle, reach minimum	.0985	-.0532	**.5949**	nd	-.0770
$cv.CA_o$	Open canopy angle, coefficient of variation of transect-level measurements, reach level	-.0818	-.0142	**-.7007**	-.0623	.0629
R_p	Potential solar radiation, reach mean, as a percentage of above-canopy total	.1314	.0487	**.6032**	.2829	-.1281
R_i	Estimated incident solar radiation, reach mean	.0690	.0487	**.6076**	.2818	-.1054
C_{S50}	Cropland, 50-m buffer distance, segment mean	-.3282	-.2020	**.5077**	.2052	-.1062
C_{Sllt}	Cropland, longitudinal linear riparian transect, segment mean	-.2716	-.2354	**.6154**	.1390	-.1271
C_{R50}	Cropland, 50-m buffer distance, reach mean	**-.5303**	-.2975	.1594	.3333	.2119
C_{R25}	Cropland, 25-m buffer distance, reach mean	**-.5152**	-.1507	.3695	nd	.2027
Wv_{S50}	Woodland, 50-m buffer distance, segment mean	.1880	-.1560	**-.7031**	-.1243	-.0837
Wv_{Sllt}	Woodland, longitudinal linear riparian transect, segment mean	.1443	-.0553	**-.6655**	-.2061	-.0115
Wv_{R25}	Woodland, 25-m buffer distance, reach mean	.3085	.1617	**-.5266**	.3103	-.2525
Wv_{Rllt}	Woodland, longitudinal linear riparian transect, reach mean	.1763	.3058	**-.5318**	.0895	-.1787
Wv_SL_{llt}	Woodland patch length, longitudinal linear riparian transect, segment mean	.2833	.1171	**-.5808**	-.2551	.0016
Wv_SFg_{llt}	Woodland gap frequency, longitudinal linear riparian transect, segment mean	.0069	-.1423	**.5608**	-.1494	.1615
Wv_RFg_{llt}	Woodland gap frequency, longitudinal linear riparian transect, reach mean	-.2631	-.4149	**.5443**	-.0202	.3192
$WwWv_{S50}$	Combined wetland and woodland, 50-m buffer distance, segment mean	.1880	-.1560	**-.6431**	-.1341	-.0345
$WwWv_{Sllt}$	Combined wetland and woodland, longitudinal linear riparian transect, segment mean	.1443	-.0553	**-.6247**	-.2087	-.0082
$WwWv_{R25}$	Combined wetland and woodland, 25-m buffer distance, reach mean	.3085	.1617	**-.5266**	-.0733	-.2849
$WwWv_{Rllt}$	Combined wetland and woodland, longitudinal linear riparian transect, reach mean	.1763	.3058	**-.5318**	.3333	-.1947
SS	Suspended sediment concentration	-.4524	**-.5238**	.0895	-.0042	-.0551

Table 25. Correlations of aquatic macrophyte and macroalgae cover with selected riparian and associated habitat variables, by study area.

[Study areas: CCYK, Central Columbia Plateau-Yakima River Basin; CNBR, Central Nebraska; DLMV, Delmarva Peninsula; GCP, Georgia Coastal Plain; WHMI, White-Miami River Basins; rank correlation computed as Spearman's *rho* (Helsel and Hirsch, 2002); nd, not determined; **bold** type indicates strong correlation (|*rho*| > 0.5). **GCP**: Only six sites in the GCP study area had non-zero extent of aquatic macrophytes and macroalgae]

Symbol	Characteristic	Rank-correlation coefficient for indicated study area				
		CCYK	CNBR	DLMV	GCP	WHMI
W_{bf}	Bankfull width, reach mean	-0.0892	0.1969	**0.6351**	nd	0.3305
S_w	Gradient, reach mean	.1504	-.1450	.0014	nd	**.5654**
CvrWd	Extent of woody debris cover, reach level	-.4985	-.3812	**-.6640**	nd	-.4154
BVC	Bank vegetative ground cover, reach mean	.1347	.4432	**.6933**	nd	-.2516
$min.CC_b$	Extent of bank canopy closure, reach minimum	-.1021	.1171	**-.6293**	nd	.0008
CC_b	Extent of bank canopy closure, reach mean	-.1079	-.2217	**-.6847**	nd	-.0238
$min.CC_c$	Extent of channel canopy closure, reach minimum	.0314	-.2141	**-.7569**	nd	-.2705
CC_c	Extent of channel canopy closure, reach mean	-.1566	**-.5413**	**-.7220**	nd	-.2951
$max.CC_c$	Extent of channel canopy closure, reach maximum	-.1751	**-.5034**	**-.6303**	nd	-.3853
$min.CA_o$	Open canopy angle, reach minimum	.2548	**.5459**	**.6537**	nd	.4441
CA_o	Open canopy angle, reach mean	.4215	**.5497**	**.7002**	nd	.2609
$cv.CA_o$	Open canopy angle, coefficient of variation of transect-level measurements, reach level	-.2051	**-.5900**	**-.8055**	nd	-.3443
R_p	Potential solar radiation, reach mean, as a percentage of above-canopy total	.1373	**.5211**	**.6749**	nd	.2179
R_i	Estimated incident solar radiation, reach mean	.1570	**.5211**	**.6762**	nd	.2010
C_{S250}	Cropland, 250-m buffer distance, segment mean	-.1676	**-.5385**	-.0573	nd	-.3200
C_{S150}	Cropland, 150-m buffer distance, segment mean	-.0998	**-.5422**	.1117	nd	-.2992
C_{S100}	Cropland, 100-m buffer distance, segment mean	-.1034	**-.5428**	.2835	nd	-.3343
C_{S50}	Cropland, 50-m buffer distance, segment mean	-.1095	**-.5062**	.3185	nd	-.3571
C_{R50}	Cropland, 50-m buffer distance, reach mean	-.0680	**-.5343**	.3585	nd	-.1326
F_b	Forest, total-basin extent	**-.5600**	.1298	.1964	nd	.1524
F_{dnr}	Forest, drainage-network riparian buffer	**-.5213**	.1143	.1471	nd	.2194
Wv_{S50}	Woodland, 50-m buffer distance, segment mean	-.2656	-.0255	-.3411	nd	**.5446**
Wv_{Sllt}	Woodland, longitudinal linear riparian transect, segment mean	-.1700	-.0099	-.2796	nd	**.5467**
Wv_{R50}	Woodland, 50-m buffer distance, reach mean	-.2742	-.0224	**-.5857**	nd	.3340
Wv_{R25}	Woodland, 25-m buffer distance, reach mean	-.2422	-.1524	**-.5943**	nd	.2268
$WwWv_b$	Forest plus woody wetland, total-basin extent	**-.5268**	.1987	.1666	nd	.1366
$WwWv_{R50}$	Combined wetland and woodland, 50-m buffer distance, reach mean	-.2742	-.0224	**-.5857**	nd	.2597
$WwWv_{R25}$	Combined wetland and woodland, 25-m buffer distance, reach mean	-.2422	-.1524	**-.5943**	nd	.2009
SS	Suspended sediment concentration	-.1940	-.1677	.1026	nd	**-.5762**

another cropland-related process. First, none of the strongly correlated cropland variables were those for the sample from the narrowest streamside buffers (that is, the longitudinal transect at 15 m from the bank). Second, the weak but negative correlations with reach-minimum velocity and day of the year, along with a weak positive correlation with extent of pool habitat ($|rho| \simeq 0.25$ for all three correlations), are consistent with the notion that hydraulic scouring by irrigation tailwater might be more important than turbidity or sedimentation as a limiting disturbance factored into the *AMp* levels there. Alternatively, agricultural herbicides from cropland would be a plausible limiting factor for *AMp* and consistent with the strong negative correlations with cropland. Kosinski (1984) reported that pesticides altered algal biomass in agricultural streams, and their toxicity possibly may have hindered macroalgal growth in the CNBR. Herbicides have been frequently detected in CNBR streams generally (Frenzel and others, 1998); and during July 2003, five different herbicides were detected in Platte River samples collected downstream from the NEET CNBR study area (Hitch and others, 2004). With regard to the hydraulic scouring alternative, an analysis of LS linear regression models using standardized (*z*-score) values for the explanatory variables (C_{S150}, CA_o, *min.V*, and *SS*) for the CNBR sites indicated that reach-minimum velocity was about four times more effective than *SS* (partial slope coefficients of -0.38 and -0.092, respectively) as the third predictor of *AMp* in tandem with segment-level cropland extent (C_{S150}) and CA_o.

Among the GCP sites, only six sites had non-zero values for *AMp*. The low values of *AMp* likely were the result of the dense canopy shading that characterized GCP streams (table 5).

Within the WHMI study area, *AMp* was correlated strongly with steepness of stream gradient (S_w), indicators of riparian woodland extent (Wv_{S50} and Wv_{Sllt}), and negatively (and most strongly) with suspended-sediment concentration (*SS*). *AMp* ($rho = -0.690$) and S_w ($rho = -0.739$) also were correlated negatively with the estimated percentage of the stream bottom covered by sand-size or finer particles, and were strongly correlated with the estimated percentage of the stream bottom covered by particles coarser than sand ($rho = 0.799$ for *AMp*, and $rho = 0.597$ for S_w). Thus, it appears that macrophyte or macroalgae growth in WHMI streams may be limited by turbidity or sedimentation, and benefited by steep reaches that have relatively stable substrates.

Greater exposure of the channel to sunlight was correlated with larger values of *AMp* at DLMV sites, as indicated by strong positive correlations with canopy openness (CA_o), insolation (R_i and R_p), and channel width (W_{bf}), and negative correlations with channel shading (fig. 16) and bank shading variables. These DLMV correlations between channel openness or shading and *AMp* were among the strongest relations found between aquatic biology and riparian habitat in this study. Slightly weaker negative correlations of *AMp* with reach-level indicators of riparian woodland extent (table 25) also are consistent with the important limiting role of local-scale stream shading.

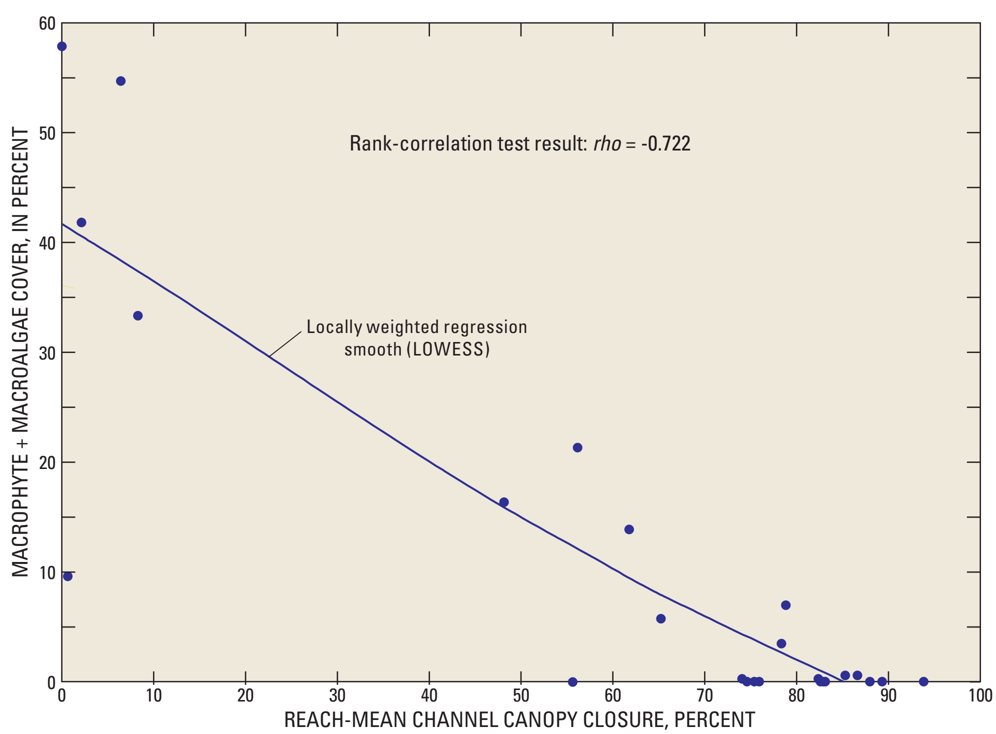

Figure 16. Relation of reach-mean aquatic macrophyte plus macroalgae extent to reach-mean channel canopy closure for Delmarva Peninsula sites.

Review of Aquatic Biological Relations to Riparian Conditions

None of the examined habitat variables were correlated strongly with concentrations of chlorophyll *a* in coarse-grained benthic habitat (*RCHL*) for more than one study area (table 17). Reach-mean current velocity was negatively correlated with *RCHL* among GCP sites. Chlorophyll *a* concentrations in GCP samples from coarse wood substrate tended to be larger at the narrower reaches where flows were generally slower. Hydraulic disturbance also was indicated as a possible explanation for the GCP results for chlorophyll *a* concentration in fine-grained benthic habitat (*DCHL)*, which was correlated strongly with reach-maximum wetted width ($max.W_w$).

Summarizing the study-unit correlations with chlorophyll *a* concentrations (*DCHL*), there were no habitat variables correlated strongly with *DCHL* for the WHMI study area. The DLMV had the most correlations between *DCHL* and habitat variables; however, the only habitat variable correlated with *DCHL* for two study areas was reach-maximum wetted width ($max.W_w$) for the CCYK and GCP sites. The positive correlation for CCYK streams may relate to open-canopy conditions, whereas for GCP sites the negative correlation may relate to greater hydraulic disturbance in wider, swifter streams. DLMV was the only study area that demonstrated the expected positive association between *DCHL* and total phosphorus (*TP*), but the correlations with *TP* and dissolved inorganic nitrogen (*DIN*) were of opposite signs. Within DLMV study reaches, the fine-grained habitats where *DCHL* was sampled may be enriched preferentially with particle-associated *TP* but not with *DIN*.

Chlorophyll *a* concentrations in seston (*SCHL*) for all sites combined were correlated strongly with concentrations of phosphorus species; however, the strength of these correlations probably was attributable, in part, to the presence of phosphorus within the algae in the seston. A multiple regression model explained 65.5 percent of the variance in *SCHL* among the combined set of sites using two nutrient species (*TP* and *DIN*) plus antecedent water temperature (T_{w30}). The regression model indicated that water temperature was the most important explanatory variable, and *DIN* was least important. Strong correlations with sestonic chlorophyll were found in more than one study area for only antecedent water temperature (CCYK and DLMV). The riparian characteristic most strongly correlated with *SCHL* was woodland extent in the segment-level riparian buffers of DLMV streams, a negative association. However, positive correlations of *SCHL* with suspended sediment (*SS)*, *TP*, and riparian cropland may indicate that factors enhancing nutrient loading to streams also may affect *SCHL* in DLMV streams.

Summarizing the correlation results among the study areas for organic material density in coarse-grained benthic habitats (*RAFD*), no variables were strongly correlated with *RAFD* for more than one study area, and only five habitat variables were correlated strongly with *RAFD* for any study area. Two of those variables were riparian characteristics (potential insolation and segment-level woodland extent), and the other three variables were associated in-stream habitat characteristics (current velocity, water temperature, and pool habitat extent). With regard to organic material density in fine-grained benthic habitats (*DAFD*), only three habitat variables were correlated strongly with *DAFD* for any study area. Two of those variables were riparian characteristics (vegetative ground cover on banks and the frequency of gaps in reach-level woodland), whereas *DIN* was correlated strongly with *DAFD* for GCP sites. The lack of any consistent pattern in the study-unit correlations of habitat characteristics with organic material density may indicate that *DAFD* and *RAFD* are not generally sensitive to nutrient enrichment in small agricultural streams. However, for GCP sites, where *DIN* concentrations were small relative to those of the other study areas, the levels of *DIN* and *DAFD* likely would have been higher were it not for the effects of woody wetland margins along most streams, as reported by Scott and others (2007).

There were no habitat characteristics that correlated strongly with algal biovolume in rock or wood samples (*RBV*) from multiple study areas. Only one strong correlation was found within any of the four study areas other than in the GCP. One possible reason that so few correlates with biovolume were found for coarse-grained benthic samples could be that another unmeasured limiting factor, such as a toxic chemical(s), was the dominant control on biovolume. For example, Kosinski (1984) reported that pesticides altered algal biomass in agricultural streams.

Summarizing the study-unit specific results for algal biovolume in depositional habitats (*DBV*), only one riparian habitat characteristic, cropland extent, was correlated strongly with *DBV* among two study areas, but the relation was positive for DLMV and negative for CCYK. *DBV* was correlated strongly to multiple habitat characteristics only for the DLMV study area. Cropland proximity and light availability appear to be the dominant underlying factors affecting algal biovolume in fine-grained depositional benthic habitats of the DLMV study reaches. Limitation of benthic algae by sediment (as in CNBR) or other factors associated with riparian cropland (as in CCYK) were indicated by negative correlations with *DBV*.

Light availability and channel shading were correlated strongly with aquatic macrophyte or macroalgae extent (*AMp*) for all sites combined, and among the CNBR and DLMV sites in particular. These DLMV relations with *AMp* (positive correlation with light availability and negative correlation with shading) were among the strongest relations found between aquatic biology and riparian habitat in this study. An inverse relation between *AMp* and riparian woodland extent at the basin level (F_{dnr}) indicated that nutrient filtering or uptake in the riparian woodland buffer and (or) channel shading may have limited macrophyte or macroalgae growth at CCYK sites. Macrophyte or macroalgae growth in WHMI streams may be limited by turbidity or sedimentation, and benefited by coarse-grained, relatively stable substrates.

Overview. Summarizing across all biological response variables, the riparian habitat characteristics that evidenced a strong relation within individual study areas most frequently were insolation exposure, bank vegetative ground cover, and segment-level extents of woodland and cropland. Each of these habitat characteristics was correlated strongly with a biological response in four or more study-area level instances (table 17), though this does not mean those instances occurred in four different study areas. Associated in-stream habitat characteristics that were correlated with biological responses in four or more study-unit instances were current velocity and water temperature.

Differences between study areas in terms of nutrient and suspended sediment concentrations, or riparian LULC, paralleled study-area differences for some biological responses. For example, for chlorophyll concentrations in periphyton samples, GCP sites had both the most extensive riparian wetlands and shading and the smallest concentrations of *DCHL* and *RCHL*. For chlorophyll in seston in relation to concentrations of phosphorus species, GCP sites had the smallest mean concentrations of both *SCHL* and *TP* and the CNBR means for both variables were the highest. These parallel study-area contrasts produced strong correlations in the overall data set, but the corresponding correlations seldom were found within more than one or two study areas. Short and others (2005) also found that strong study-area contrasts made it difficult to compare ecological effects involving stream habitat in contrasting environments and noted the overwhelming effects of some geologic and climatic differences between study areas.

Summary and Conclusions

Identifying and quantifying relations between biological responses and nutrients in stream environments is often confounded by the interaction of physical and biological factors. Physical factors, including both in-stream and riparian habitat characteristics, that limit biomass or otherwise regulate biological processes have been identified in previous studies. Linking the ecological significance of nutrient enrichment to habitat or landscape factors that could allow for improved management of streams has proved to be a challenge in many regions, including agricultural landscapes where many ecological stressors are strong and the variability among watersheds is typically large.

Responding to the interest in nutrient enrichment of streams and the factors and processes affecting it, the U.S. Geological Survey (USGS) National Water-Quality Assessment Program (NAWQA) began in 2001 a study of the effects of nutrient enrichment on agricultural stream ecosystems (NEET). The primary objective of the study was to determine how biological communities and processes respond to varying levels of nutrient enrichment in agricultural streams from contrasting environmental settings. Study areas within five NAWQA study units—Central Columbia Plateau and Yakima River Basin (CCYK), Central Nebraska (CNBR), Delmarva Peninsula (DLMV), Georgia Coastal Plain (GCP), and White, Great and Little Miami River Basins (WHMI)—were selected to represent a cross section of agricultural landscapes across the U.S.

This report addresses five primary questions through the examination of a variety of riparian habitat and associated characteristics.

(A) How do the study areas differ with respect to riparian habitat, including land use?

(B) How does spatial scale affect land-use and land-cover characteristics of riparian buffers?

(C) What subset of habitat characteristics captures most of the variability in riparian and associated habitat conditions, including land use?

(D) What riparian and associated habitat characteristics best explain nutrient concentrations?

(E) What riparian and associated habitat characteristics best explain aquatic biological responses?

Riparian variables examined at sites within all five study areas included the extent or spatial structure of general land use and land cover types, and riparian-habitat features measured either onsite (reach and transect scales) or determined by geographic information system (GIS) analysis and interpretation of aerial photographs (reach, segment, and basin scales).

Riparian characteristics were sampled in 2003 in the CCYK and CNBR study areas, and in 2004 in the GCP, DLMV, and WHMI study areas. This report examined results of analyses of samples, observations, and measurements at 141 sites ranging from 25 to 30 sites per study area that were selected on the basis of an initial stratification of the population of stream segments from the National Hydrography Dataset (NHD). Stratum assignments were based on expected stream size, drainage-basin area, land use and land cover (LULC) types, soils, ecoregions, and estimated nutrient loadings.

Physical habitat characteristics data were collected for a multi-level hierarchy of spatial scales—basin, segment, reach, and transect levels. Biological data were collected at the reach scale, whereas water-quality data were collected at the channel-transect level. Biological measures used as response variables in this report included algal biomass (as chlorophyll *a*), organic material (as ash-free dry mass), algal biovolume, and aquatic macrophytes plus macroalgae cover.

Basin-scale terrestrial habitats were summarized using GIS to calculate LULC percentages for the total drainage basin and for the riparian buffer that extended 90-m in both directions from the stream. The segment-scale variables were calculated using GIS overlays of streamside buffer areas that extended various distances (50 to 250 m) from the stream segment, with segment length defined by the base-10 logarithm of the upstream drainage area. Available data for segment LULC had been delineated and classified from digital orthophoto quadrangles. Reach-level data were collected for a stream reach having length equal to 20 times the bankfull width, and usually located adjacent to the water-quality sampling site. Reach-level buffer distances of 25 and 50 m defined local-scale riparian areas for LULC analysis. Two additional riparian-buffer transects were located by using a 15-m offset distance from both streambanks, and LULC was sampled along these two linear transects at both the segment and reach scales. Reach-scale data for other riparian and stream physical habitat variables were downloaded from the USGS Biological Transactional Database for NAWQA ecological data. As a quality-assurance step, differences between reach and segment levels in woodland extent within the riparian areas bounded by the 50-m buffer were tested.

Because the study was focused on summer stable-flow periods, each site was visited twice to collect water samples for nutrient analysis. Samples were collected approximately one month prior to the biological sampling, and then again during the biological sampling. Water temperature, discharge, turbidity, suspended sediment, pH, and dissolved oxygen were either measured in the field at the time of sampling or determined later in the laboratory (suspended sediment concentration).

Univariate statistical summaries of individual habitat or response variables used measures of central tendency (median or mean) and dispersion about the center (coefficient of variation or selected percentiles). For comparing two groups of sample data, in most cases, the data sets were independent and the Wilcoxon rank-sum test was used. For paired data, the Wilcoxon signed-rank test was used. Evaluations of correlation strength used Spearman's rank correlation coefficient, *rho*. Values of *rho* greater than 0.5 were referred to as strong correlations, whereas values less than 0.5 were not discussed as providing independent evidence for a bivariate correlation.

The riparian habitat and associated characteristics were categorized into 22 groups of habitat variables—11 groups of LULC characteristics including basin, segment, and reach levels, 5 groups of hydrogeomorphic characteristics, 4 groups of riparian characteristics measured onsite, and 2 groups representing in-stream cover. A set of 29 variables was selected as representing 20 habitat categories, and these variables were analyzed using principal components analysis (PCA). With GCP sites having been excluded as a separable cluster in the multivariate distribution (causing a bimodal, non-normal distribution), PCA with axis rotation (factor analysis) provided additional understanding of the underlying interrelations among the selected set of habitat variables. Loadings on the principal factors indicated a minimum number of variables that accounted for most of the information present in the riparian data set.

Question (A)—Study-unit contrasts in riparian habitat. The mean percentages of basin area in cropland and pasture (C_b) ranged from 34 to 90 percent among the study areas, and averaged 56 percent overall. Forest plus woody wetland, when combined, had an average extent of 22 percent at the basin scale, but study-unit means fell into two groups: GCP and DLMV sites had extensive woodland cover (50 and 40 percent, respectively), whereas woodland was relatively sparse (3 to 14 percent) in the watersheds of the other three study areas.

Within the nominally 90-m buffer zone along the basin drainage network, the land-cover mosaic was more mixed in composition than for the total basin. The extent of cropland and pasture within these riparian buffers (C_{dnr}) had an overall mean of 44 percent, and mean values of C_{dnr} ranged from 17 to 78 percent among the study areas. In contrast, the overall mean extent of forest plus woody wetland in riparian buffers was 35 percent, and study-unit means ranged from 5.4 percent (CNBR) to 76 percent (GCP).

Geomorphologically, study sites in the CCYK and WHMI had steeper stream gradients, typically had longitudinal profiles exhibiting riffle-and-pool morphology, and wetted channels were wider than the sites of the other study areas as a group. Study sites in the DLMV, GCP, and WHMI study areas had slower (but more variable) mean current velocity and smaller *Froude* than did sites in the CCYK and CNBR study areas.

Bank canopy closure (CC_b) was greater in the GCP reaches than in any other study area, and was least for the CCYK and CNBR sites. The canopy closure at mid-channel also was greatest for GCP sites and the conditions at western sites were significantly more open than for eastern sites. GCP sites were not significantly different from WHMI sites in channel canopy closure, but the GCP sites did receive less insolation exposure than WHMI sites.

Comparisons of median values of woodland extent between reach- and segment-levels for the riparian buffer extending 50 m to either side of the stream indicated no significant differences for any study area. For less extensive riparian land-cover types, however, reach- and segment-level LULC indicators were significantly different, as they were for all measured indicators of patch structure. These results suggest that the reach length used for this study generally is not long enough to accurately represent both the overall composition and patch structure that characterizes the riparian areas along small, agricultural streams. Implications for stream ecologists may include the need to sample longer reaches or supplementing field sampling with analyses of aerial photography to characterize longer segments of the riparian corridor when study objectives require accurate data for minor cover types or patch structure.

At the reach level of the habitat hierarchy, cropland was absent from 75 percent of GCP riparian zones, the interquartile range of cropland ranged from 2 to at least 33 percent in the CNBR and WHMI riparian areas, and riparian cropland extent was intermediate for the CCYK and DLMV sites.

Grassland is characteristically absent from the GCP, DLMV, and WHMI riparian zones, whereas in both western study areas it is typically present but not dominant in most riparian areas. For the GCP sites, woody wetlands are the natural riparian vegetation, and were more extensive there than for any other study area. Wetlands were characteristically absent in the CCYK, CNBR, and DLMV riparian zones, whereas in the WHMI study area they are commonly present but not dominant in most riparian areas. Other types of woodland cover are characteristically sparse in the GCP riparian buffers, but are dominant in the DLMV and WHMI riparian areas, and intermediate for the western study areas.

Question (B)—Spatial scale effects on LULC of riparian buffers. Frequently noted was a scale-related pattern in which the areal extent of a LULC category increased (or decreased) consistently as the analysis buffer width increased. Correlations between cropland extent for the total basin and cropland extent within varying riparian buffer areas were weakest for the narrow reach-level buffers and increased steadily as buffer area widened and scale increased. A similar pattern was noted for grassland extent, but, for all scales examined, riparian woodland extent was correlated strongly with its total-basin extent. The correlations between drainage-network riparian-buffer extent of land cover and total-watershed extent of that land cover were strong for each of the three LULC types included in the multivariate analyses—cropland and pasture, woody wetland, and woodland.

Riparian woody wetland plus woodland combined extent was correlated with its total-basin extent at all spatial scales, and most strongly so at the drainage-network scale. To the extent that riparian woodland is the most important LULC type affecting algal-nutrient relations, the correlations indicated that basin characteristics might be effective surrogate predictors of riparian effects. But the results also indicated that basin-level cropland was not an accurate surrogate for riparian cropland extent except at the drainage-network scale.

Correlations with woodland extent within 50 m of the channel (reach- and segment-level data) decreased in strength as the compared band of riparian buffer shifted beyond the first 50 m from the channel, becoming negligible for areas beyond 100 m from the channel. For all sites draining less than 60 km^2, all segment level woodland-extent variables were correlated with each other and with total-basin extent of woodland, whereas the reach-level woodland extent was not strongly correlated with woodland extent in bands more than 50 m distant from the stream. Results for sites with larger drainage basins indicated that, for many of the studied agricultural streams, the riparian buffer may include a heterogeneous mix of riparian and upland land covers when the summarized buffer area extends more than about 50 to 100 m from the streambank, depending upon basin or stream size.

Differences between basin-scale and segment-level extents of cropland within the riparian buffer areas were significant for all segment-level buffer widths among the GCP and WHMI sites. But for the CNBR and DLMV study areas, the differences were significant for buffer widths of up to 100 m. In the CNBR and WHMI study areas, cropland percentage more than doubled as the buffer width increased from 25 to 50 m, whereas lesser increases were noted for the CCYK and DLMV areas.

Question (C)—Subset of habitat variables to characterize riparian buffers. Categorization, data reduction, and analysis by principal components and factor analysis yielded results useful to address this report purpose. The first principal factor accounted for 24.4 percent of the total variance in the analyzed data—29 variables for 105 sites, combining data from four study areas. The habitat measures that loaded most strongly on factor 1 (*F1*), which could be considered the best indicators of riparian canopy shading among the indicators measured for this study, were reach-mean open-canopy angle (CA_o) and channel canopy closure (CC_c). The latter measure was added specifically for this study, supplemental to the standard NAWQA habitat protocol. One reason that the standard protocol did not include the mid-channel sampling point for CC_c may have been that the expected stream width of NAWQA ecological sampling sites was larger than many of those used for the NEET study. However, several of the variables most closely associated with *F1* (for example, percentage of woodland cover within narrow riparian buffers) are not among those routinely measured for physical habitat characterization of NAWQA ecological sampling sites. Similarly, among the variables most strongly related with *F2*, none of these LULC indicators are routinely measured for physical habitat characterization of NAWQA ecological sampling sites. Given that the two leading factors together contained about 37 percent of the total variance in the 29-variable data set, it appears that studies focusing on riparian conditions might benefit from supplementing the standard NAWQA protocol for habitat characterization.

F2 loadings were largest for two segment-level cropland extent metrics, followed by another segment-level variable, mean length of gaps in riparian woodland along the longitudinal transect. Thus, factor 2 was interpreted as an index of cropland within riparian buffers. Factor 3 accounted for only 11.5 percent of the variance, but had very strong loadings from width-to-depth ratio and mean wetted width.

In summary, the set of variables that appears to best characterize riparian buffers of four study areas included mid-channel measures of canopy shading, riparian cropland extent for the narrow buffer (15 m) and 150-m buffer, and measures of the patchiness of woodland cover in the narrow buffer (patch length and gap frequency). LULC metrics calculated for riparian buffers, particularly at the segment scale, were more correlated with the principal modes of variation in the overall habitat data set than was LULC extent for the total basin drained by each site. The factor analysis of GCP data indicated that riparian LULC (wetland extent in particular) and channel shading correspond to dominant modes of variability in riparian habitat within this study area, even as they had distinguished the GCP sites from the other four study areas in the PCA of the combined data set.

Relation of Nutrients to Habitat Characteristics

This subsection summarizes results concerning the fourth report purpose. For nitrogen species, the correlations with riparian cropland were more widespread at the basin scale, where the correlation with either cropland or row-crop extent was strong in three study areas for both total nitrogen (*TN*) and dissolved inorganic nitrogen (*DIN*). For *TN* and *DIN*, riparian characteristics correlated with both nitrogen species among multiple study areas were basin-level extents of riparian cropland (C_{dnr}) and bank vegetative cover. The correlations with these riparian variables underscore the importance of agricultural land-management and conservation practices for reducing nitrogen delivery from near-stream sources.

The capacity for wetland to reduce nitrogen concentrations in streams was not consistently confirmed in this study. For all sites combined, no strong negative correlation of wetland extent with either *TN* or *DIN* was found, and only at the basin scale were strong inverse relations found, but only for one study area (CCYK). However, when sites lacking segment-level wetlands were excluded, the negative correlation of riparian wetland extent with *DIN* among 49 sites was strong at the reach and segment levels. These results are indicative of the role played by riparian wetland vegetation in removing dissolved nutrients from soil water and shallow groundwater passing through riparian zones.

For phosphorus species with all sites included, riparian wetland extent was negatively correlated with both total and orthophosphate phosphorus (*TP* and *OP*, respectively) at basin and reach scales, and segment-level riparian cropland was positively correlated for all buffer widths.

For phosphorus species, the only reach-level habitat characteristics correlated with both phosphorus species at even one study area each were insolation and antecedent water temperature. Among the study-unit relations with phosphorus concentrations, the only variable correlated strongly with *TP* for three study areas was a non-riparian characteristic (*SS*), and *OP* was not correlated strongly with any variable in multiple study areas. *TP* concentrations commonly are correlated with suspended-sediment concentrations, but positive correlations of *TP* with *SS* and negative correlations with insolation could indicate that light limitation of in-stream processing of phosphorus may be the most common riparian control on phosphorus concentrations.

Nutrient concentrations were correlated with the extent of riparian cropland for all sites combined. In particular, segment-level extent of cropland within the 250-m riparian buffer was correlated strongly with all four nutrient species examined in this report.

Relation of Aquatic Biology to Riparian Habitat

None of the examined habitat variables were correlated strongly with concentrations of chlorophyll *a* in coarse-grained benthic habitat (*RCHL*) for more than one study area. Reach-mean current velocity was negatively correlated with *RCHL* among GCP sites. Hydraulic scour also was indicated as a possible explanation for the GCP results for *DCHL*. The only habitat variable correlated with *DCHL* for two study areas was reach-maximum wetted width ($max.W_w$). The DLMV study area had the most correlations between habitat variables and chlorophyll *a* concentrations in fine-grained benthic habitat.

For the combined data set, only sestonic chlorophyll *a* concentrations were positively correlated with phosphorus concentrations, whereas none of the biological responses showed a strong correlation with either nitrogen species. Strong positive correlations with sestonic chlorophyll *a* concentration (*SCHL*) were noted for antecedent water temperature (CCYK and DLMV). Woodland extent in segment-level riparian buffers was inversely associated with *SCHL* for DLMV streams as the most strongly correlated riparian characteristic, followed by insolation exposure, also for DLMV sites.

For the combined data set, strong relations between riparian habitat characteristics and organic material density in benthic habitats were sparse, limited to a negative correlation between woody wetland extent at the basin scale and organic material in coarse-grained habitat (*RAFD*). For GCP sites, where *DIN* concentrations were small relative to those of the other study areas, the levels of *DIN* and *DAFD* likely would have been higher were it not for the effects of woody wetland margins along most streams. The lack of any consistent pattern in the study-unit correlations of habitat characteristics with organic material density may indicate that *DAFD* and *RAFD* are not generally sensitive to nutrient enrichment in small agricultural streams.

Only one strong correlation with algal biovolume in rock or wood samples (*RBV*) was found within any of the four study areas other than the GCP. Among GCP sites, *RBV* was less where reach-mean and -minimum current velocities were swifter, possibly indicating an effect from hydraulic disturbance. Cropland proximity and light availability appear to be the dominant underlying factors affecting algal biovolume in fine-grained depositional benthic habitats (*DBV*) of the DLMV study reaches. Limitation of benthic algae by sediment (as in CNBR) or other factors associated with riparian cropland (as in CCYK) were indicated by negative correlations with *DBV*.

Light availability and channel shading were correlated strongly with aquatic macrophyte or macroalgae extent (*AMp*) for all sites combined, and among the CNBR and DLMV sites in particular. An inverse relation between *AMp* and riparian woodland (F_{dnr}) extent indicated that nutrient filtering or uptake in the riparian buffer and (or) channel shading may have limited macrophyte or macroalgae growth at CCYK sites. Macrophyte or macroalgae growth in WHMI streams may be limited by turbidity or sedimentation, and benefited by coarse-grained, relatively stable substrates. Channel shading appeared to play the dominant role in controlling *AMp* cover in the DLMV where correlations between channel openness or shading and *AMp* were among the strongest relations found between aquatic biology and riparian habitat in this study.

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Appendix 1. Correlations of the total and riparian extents of woodland for selected riparian buffers, defined by habitat hierarchical level and by riparian-buffer distance, by study area or drainage-area class.

[Coefficients tabled are Spearman's rank-correlation strength, *rho*. Spatial buffer areas are bounded by lines paralleling the stream at the indicated distances from the channel margin; n, number of included sites per study area; **bold** type indicates strong correlation (|*rho*| > 0.5); –, not analyzed or redundant value]

Level within stream habitat hierarchy	Riparian buffer distance (meters from channel) or summary area	Riparian buffer or summary area, at segment level except where otherwise indicated				
		Reach level, 0–25 meters	0–50 meters	50–100 meters	100–150 meters	150–250 meters
Central Columbia Plateau-Yakima River Basin study area (n = 29)						
Segment	0–50	**0.762**	–	–	–	–
Segment	50–100	**.501**	**0.626**	–	–	–
Segment	100–150	.416	**.517**	**0.835**	–	–
Segment	150–250	.156	.318	**.576**	**0.734**	–
Basin	Total basin, including upland	.481	**.630**	.227	.233	0.206
Central Nebraska study area (n = 28)						
Segment	0–50	0.447	–	–	–	–
Segment	50–100	.195	**0.836**	–	–	–
Segment	100–150	.065	**.705**	**0.867**	–	–
Segment	150–250	.091	**.621**	**.800**	**0.858**	–
Basin	Total basin, including upland	.193	.395	.325	.400	0.403
Delmarva Peninsula study area (n = 25)						
Segment	0–50	**0.746**	–	–	–	–
Segment	50–100	.230	**0.669**	–	–	–
Segment	100–150	-.188	.231	**0.774**	–	–
Segment	150–250	-.395	-.092	.466	**0.812**	–
Basin	Total basin, including upland	-.226	-.172	.123	.305	0.481
Georgia Coastal Plain study area (n = 29)						
Segment	0–50	0.222	–	–	–	–
Segment	50–100	.048	**0.792**	–	–	–
Segment	100–150	.008	**.505**	**0.737**	–	–
Segment	150–250	.035	-.075	.095	**0.640**	–
Basin	Total basin, including upland	.151	-.216	-.077	.274	0.461
White-Miami River Basins study area (n = 30)						
Segment	0–50	**0.512**	–	–	–	–
Segment	50–100	-.016	**0.579**	–	–	–
Segment	100–150	-.091	**.507**	**0.928**	–	–
Segment	150–250	-.184	.436	**.844**	**0.932**	–
Basin	Total basin, including upland	-.090	.399	.429	.327	0.327

Appendix 1. Correlations of the total and riparian extents of woodland for selected riparian buffers, defined by habitat hierarchical level and by riparian-buffer distance, by study unit or drainage-area class—Continued.

[Coefficients tabled are Spearman's rank-correlation strength, *rho*. Spatial buffer areas are bounded by lines paralleling the stream at the indicated distances from the channel margin; n, number of included sites per study area; **bold** type indicates strong correlation (|*rho*| > 0.5); –, not analyzed or redundant value]

Level within stream habitat hierarchy	Riparian buffer distance (meters from channel) or summary area	Riparian buffer or summary area, at segment level except where otherwise indicated				
		Reach level, 0–25 meters	0–50 meters	50–100 meters	100–150 meters	150–250 meters
Drainage area greater than 60 km^2 and less than or equal to 120 km^2 (n = 30)						
Segment	0–50	**0.804**	–	–	–	–
Segment	50–100	.095	**0.504**	–	–	–
Segment	100–150	-.341	-.028	**0.685**	–	–
Segment	150–250	-.420	-.226	.475	**0.896**	–
Basin	Total basin, including upland	-.377	-.190	.304	**.520**	0.457
Drainage area greater than 120 km^2 and less than or equal to 200 km^2 (n = 33)						
Segment	0–50	**0.743**	–	–	–	–
Segment	50–100	-.158	0.253	–	–	–
Segment	100–150	-.454	-.144	**0.802**	–	–
Segment	150–250	**-.505**	-.332	**.679**	**0.917**	–
Basin	Total basin, including upland	-.446	-.294	.340	**.613**	**0.674**

Appendix 2. Correlations of reserved riparian habitat variables with scores from factor analysis of Georgia Coastal Plain data.

[F*j*, principal factor *j*; GCP, Georgia Coastal Plain study area; rank correlation computed as Spearman's *rho* (Helsel and Hirsch, 2002); **bold** type indicates strong correlation (|*rho*| > 0.5); –, not calculated (no variance); nc, very weak correlation, that is, magnitude of Spearman's *rho* was less than 0.05; CV, coefficient of variance]

Variable symbol	Characteristic	Coefficient of rank correlation with indicated factor scores			Number of GCP sites summarized
		F1 score	*F2* score	*F3* score	
Solar insolation					
$min.R_p$	Potential solar radiation, minimum	0.2059	-0.1370	-0.2241	26
R_p	Potential solar radiation, mean	nc	nc	**-.7241**	26
$max.R_p$	Potential solar radiation, maximum	-.0510	.0917	**-.5935**	26
$min.R_i$	Estimated incident solar radiation, minimum	.2059	-.1370	-.2241	26
R_i	Estimated incident solar radiation, mean	nc	nc	**-.7250**	26
$max.R_i$	Estimated incident solar radiation, maximum	-.0510	.0917	**-.5935**	26
Other reach-level habitat indicators					
$min.CC_b$	Extent of bank canopy closure, reach minimum	0.1215	-0.0795	0.2761	26
$max.CC_c$	Extent of channel canopy closure, reach maximum	.1467	nc	.3333	26
$max.CA_o$	Open canopy angle, reach maximum	-.1727	nc	**-.6595**	26
$cv.CA_o$	Open canopy angle, reach CV of transect-level measurements	nc	-0.2144	**.6235**	23
Land-use and land-cover indicators					
C_{dnr}	Cropland and pasture, drainage-network riparian buffer	0.4065	nc	0.2916	26
G_b	Grassland, total-basin extent	-.0680	-0.2588	.4058	26
G_{dnr}	Grassland, drainage-network riparian buffer	.2694	-.1228	.3238	26
G_{S100}	Grassland, segment-level, extent in 100-m buffer	.1453	nc	-.0615	26
G_{S50}	Grassland, segment-level, extent in 50-m buffer	.0667	.1200	.1200	26
G_{R25}	Grassland, reach-level, extent in 25-m buffer	–	–	–	26
Ww_{dnr}	Woody wetland, drainage-network riparian buffer	-.1460	-.2171	.1836	26
F_{dnr}	Forest, drainage-network riparian buffer	-.2533	.1077	-.2971	26

Appendix 3. Multiple linear regression model for chlorophyll *a* in seston (*SCHL*).

Command line usage for S-Plus "lm" routine:

```
xx.lm7a <- lm(formula = log.SESCHL ~ log.XTP.z + AV.TEMP.30.z + qtrt.XDIN.z ,
  data = merg8.HDAS.ripar.lulc[merg8.HDAS.ripar.lulc$SAMPL != "115154",],
  na.action = na.exclude)
```

Output from S-Plus "lm" routine:

```
Coefficients:
               Value Std. Error t value Pr(>|t|)
 (Intercept)  0.3146  0.0393     8.0049  0.0000
   log.XTP.z  0.2880  0.0494     5.8276  0.0000
AV.TEMP.30.z  0.3833  0.0477     8.0292  0.0000
 qtrt.XDIN.z -0.1074  0.0412    -2.6073  0.0103

Residual standard error: 0.4242 on 114 degrees of freedom
Multiple R-Squared: 0.6638      Adjusted R-squared: 0.655
F-statistic: 75.04 on 3 and 114 degrees of freedom, the p-value is 0
22 observations deleted due to missing values

Residuals:
   Min      1Q   Median     3Q   Max
 -0.97 -0.2844 -0.01278 0.2651 1.207

> summary(xx.lm7a$fitted.values)
        Min.     1st Qu.      Median        Mean     3rd Qu.        Max.
 -0.78812936 -0.02801619  0.16477734  0.34252067  0.65873686  1.70277191
```

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Zelt and Munn— **Riparian and Associated Habitat Characteristics in Selected Agricultural Areas, United States, 2003–04**—Scientific Investigations Report 2009–5224