

Landscape Structure and Nutrient Budgets in an Agricultural Watershed, Southwest Ohio¹

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ABSTRACT. Managing for uncultivated lands in agricultural watersheds may be a cost effective way to improve surface water quality. For this study, landscape structure and nutrient (N, P) budgets were compared in seven first-order basins of Marshall's Branch watershed, Preble County, OH. Row crops were the dominant land use in all basins. Three basins had greater than 25% of stream buffers forested and nitrate concentrations below average. Four basins had higher pasture and residential land use proportions and phosphorus concentrations higher than average. Growing season precipitation in 1994 was low, resulting in low nutrient transport. Although no basins had net export of nutrients, trends exist that point out relationships between landscape structure and nutrient storage. Of particular importance is the strong effect small changes in forested stream buffers had on nitrogen flows in the basins, suggesting small land use changes in targeted areas can affect positive changes in basin-wide nutrient dynamics.

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INTRODUCTION

The Upper Four Mile Creek watershed in Preble County, OH, is an intensive agricultural landscape. Greater than 85% of the total land area (Medley and others 1995) and greater than 90% of the upper basin outside of Hueston Woods State Park (Vanni and others 2001) is in cultivated row crops and pasture. Water quality in streams draining the watershed is low due to high rates of erosion and associated nutrient runoff (USDA 1992; Vanni and others 2001). The Natural Resource Conservation Service (NRCS), working in cooperation with other governmental agencies, began implementing a plan in the early 1990s to ameliorate the effects of agriculture on water quality in streams and in Acton Lake, the reservoir located at the base of the watershed (Fig. 1; USDA 1992). The plan emphasizes source reduction by supporting reduced tillage systems, combined with engineering solutions such as floodwater retention basins, to store sediment. While much research focuses on best management practices of cultivated lands (see Alberts and Spomer 1985; Cooper and Gilliam 1987; Logan 1990), less is known about the buffering capacity of uncultivated lands (Correll 1991; Barrett and others 1990). Of particular interest is how the structure of these lands in the watershed influences nutrient flows.

In order to improve water quality in agricultural landscapes, the importance of implementing 'better' management practices on cultivated lands receives strong support (Barrett and others 1990; Logan 1990; McIsaac 1994). Engineering solutions such as sediment basins can also reduce loading to endpoints, such as reservoirs, by slowing in-channel flows of pollutants (USDA 1992; cf., Crasswell 1993). However, the functional role of landscape structure in interrupting flow from crop lands to streams is not fully understood (Lowrance and others

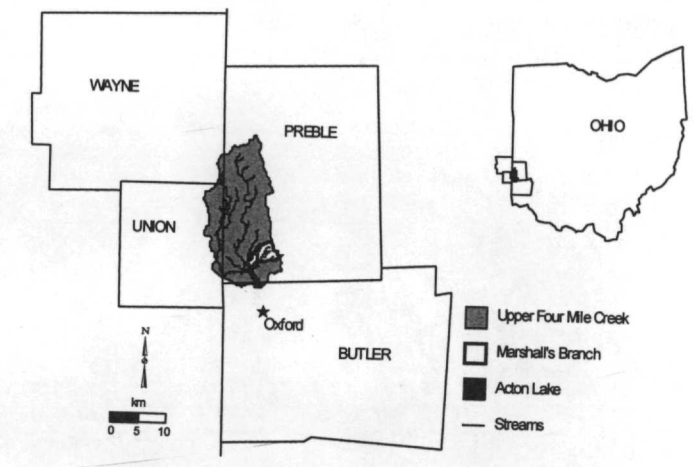


FIGURE 1. Location of the Marshall's Branch watershed in the Upper Four Mile Creek watershed in Preble County, southwest Ohio. The reservoir, Acton Lake, is located at the base of the watershed.

1984; Correll 1991). Managing uncultivated lands in watersheds may be a cost effective way to improve water quality in agricultural landscapes, and recent advances in landscape ecology highlight some important hypothesized relationships between the structural configuration of these lands and nutrient redistribution (e.g., Forman 1987; Barrett and others 1990). Proportions of uncultivated land areas, a heterogeneous distribution of uncultivated lands, and the position of uncultivated patches near streams disrupt horizontal flows and may potentially capture sediment and nutrients as they move through landscapes.

We report on a study of relationships between parameters of landscape structure and compiled nutrient budgets for small watersheds in southwest Ohio. Budgets for nitrogen and phosphorus, based on differences between inputs and outputs, were compared among first-order basins in Marshall's Branch, a sub-watershed of Four Mile Creek (Fig. 1). We hypothesized that nutrient storage, defined as a budgeted output that is less than the input, will show significant positive relationships

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with three parameters of landscape structure in uncultivated forest lands: a) land-cover proportions; b) number and configuration of different landscape patches; and c) their position along stream corridors. Differences between inputs and outputs, which are related to these attributes, should demonstrate the relative importance of landscape structure on the capture and potential storage of nutrients. Water quality may be improved in agricultural watersheds by developing management strategies that emphasize a beneficial landscape structure.

MATERIALS AND METHODS

Study Watersheds

Marshall's Branch is a 13 km² tributary watershed of Upper Four Mile Creek located in Preble County, OH (Fig. 1). Comparable to the Four Mile Creek watershed, land use in Marshall's Branch is dominated by conventional row crop agriculture (79%; Fig. 2a). The watershed drains directly into Acton Lake, which makes it an important potential contributor of non-point source pollutants to the reservoir. Seven first-order streams flow into Marshall's Branch, a second-order stream (Fig. 2b).

These sub-basins were examined as independent cases for comparison, and range in size from 45 to 366 hectares.

First-order streams have no tributaries. In this watershed they commonly drain areas of low topographic relief, dominated by Crosby-Brookston, Russell-Xenia, and Miami-Celina soil associations (Lerch and others 1969). These associations are distributed as somewhat poorly drained to poorly drained Crosby-Brookston soils in the upper basin, to well drained and moderately well drained Russell-Xenia and Miami-Celina soils. All soils are covered by a mantle of silty material, underlain by calcareous till. The topography of the basins is mainly flat uplands with more relief near streams. The highest elevation in the watershed is 335 m, and the lowest point is 263 m. Relief ratios, measured as the difference between the highest and lowest point in each basin divided by the length of the longest axis of the basin, are low. For the seven sub-basins, they range from 0.011 in Basin 9 to 0.022 in Basin 11, with a mean of 0.014. Mean slopes ranged from 1.5% in Basin 9 to 2.6% in Basin 11, with a mean of 1.7%. Overall, Marshall's Branch watershed has a mean slope of 2% and a relief ratio of 0.012.

Water Balance

Water budgets were calculated for the study year (1994) and over the long-term, using an empirical technique based on local precipitation (PPT) and average monthly temperature (Thorntwaite and Mather 1955). Potential evapotranspiration (PET) was calculated from monthly average temperature and corrected for latitude. When PPT is greater than PET, energy is the limiting factor and actual evapotranspiration (AET) is equal to PET. Water surplus is available for runoff from the watershed. In months where PET exceeds precipitation (PPT) the deficit is made up by a withdrawal of soil water and AET equals PPT plus the change in stored soil moisture. The moisture deficit is the difference between PET and AET. The annual water balance is the sum of all monthly moisture surpluses and deficits. The water budget for 1994, based on data from the Miami University Ecology Research Center, was compared with local long term average values (1945-1993) computed from archival data compiled by the Miami Conservancy District. Both stations are near Oxford, OH, or approximately 10 km from the study watershed (Fig. 1).

Nutrient Budgets

Inputs were considered from environmental (precipitation) and agricultural (fertilizer and manure) sources for the 1994 growing season. Precipitation measurements from Miami University Ecology Research Center (ERC) were considered to apply equally to each study basin, and nutrient loads from precipitation (NADP/NTN 1995) depended on basin areas. We compiled estimates of fertilizer inputs for crops from data available in the Agricultural Management Profit Survey (AMPS; Mull and Ramsey 1994). These nutrient application data were gathered from 81 corn and 16 soybean operations in Preble County and were averaged for each crop, respectively. Car surveys executed in 1994 by Preble Soil and Water Conservation District in the

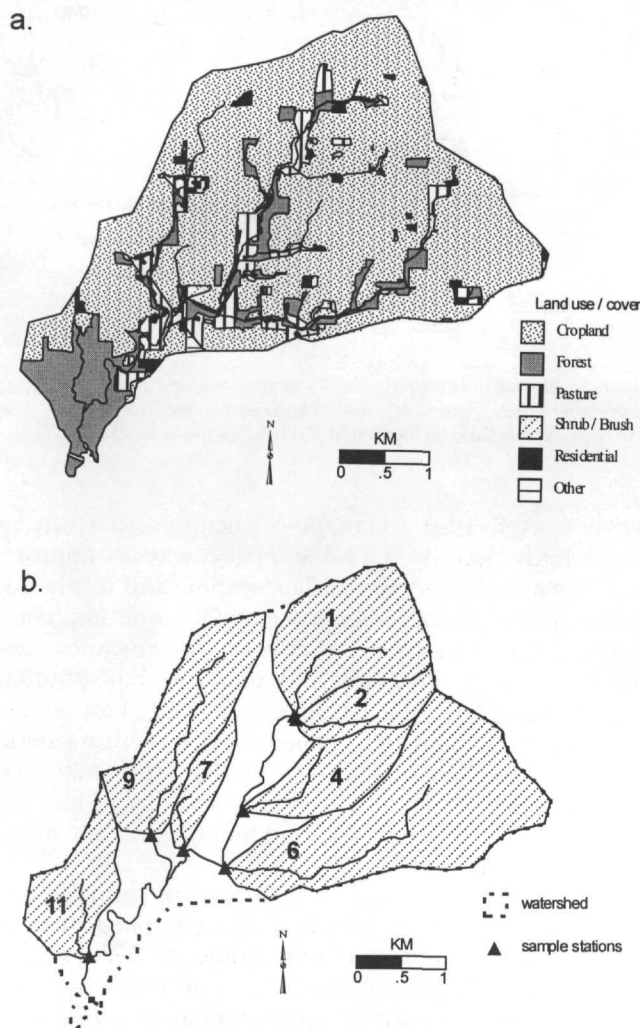


FIGURE 2. The Marshall's Branch study area, showing: a) 1989 land cover based on aerial data from the Ohio Department of Natural Resources; and b) the seven study basins (numbers corresponded with a larger study in the watershed) and the sample locations (triangles).

Upper Four Mile Creek watershed, including Marshall's Branch, show 47.9% of cropland area planted in corn and 38.7% planted in soybeans. These crop proportions were multiplied by total cropland area for each basin. Nutrient inputs were calculated as fertilization amount multiplied by crop area. Nutrient inputs from livestock were based on published coefficients for grazed pasture lands in the Midwest (see Beaulac and Reckhow 1982) multiplied by pasture area in each study basin.

Outputs were estimated by crop yields and measurements of nitrogen and phosphorus in surface water. Crop yield data were gathered from the 1994 AMPS report for harvests of corn and soybeans. Removal rates for corn and soybeans harvested were gathered from the literature and AMPS data (Lowrance 1992; Mull and Ramsey 1994). Nutrient output was calculated as removal rate multiplied by area of crop.

Water sampling sites were established at the base of the seven first order streams (Fig. 2b). Water samples were collected weekly for as long as the streams held water during the 1994 growing season (May-October) to determine low flow nutrient outputs, and at random times (i.e., as soon as the basin was reached), during or immediately following significant rainfall events. These samples were analyzed and compared for soluble nitrate and total nitrogen concentration (Crumpton and others 1992), and total particulate and soluble reactive phosphorus concentration (Stanton and others 1974).

Total nitrogen and phosphorus concentrations (mg/l) were multiplied by runoff in order to convert the measures to unit loads (kg/ha) for the studied growing season. Runoff was measured at a permanent gauging station on Marshall's Branch. These data, though provisional because of a relatively short (1+ year) collection period, provided the best estimate for the loading calculations and a measure comparable with long-term data on the water balance. Once the unit export coefficients of all inputs and outputs in each study basin were calculated, the budget was summed. The sum of all nutrient inputs divided by the sum of outputs was calculated as the storage ratio (IO) for each basin.

Landscape Analyses

Relations between land cover and nutrient storage were analyzed using a geographic information system (GIS). Land use/land cover was digitized for the watershed from 1989, 1:24000 scale Ohio Department of Natural Resources maps (see Fig. 2) and classified into six major types for analysis: cropland; pasture; forest, including mostly mature secondary growth woodlots; shrub/brush; residential; and other (e.g., ponds, cemeteries, and junkyards) (Lucas 1998).

Landscape structure was defined by the proportion, configuration, and position of land use types, particularly forests, within the study basins. Land-cover proportions were measured as the percentage of each land use in the respective basin. Land use maps for each study basin were then rasterized into 3 m × 3 m grid cells. Parameters of landscape configuration were measured for raster data using a spatial analysis program developed at the Rocky Mountain Range and Experiment Station (Flather

and others 1992): total patch number; patch density (# patches/ha); and an index of contagion (C; see O'Neill and others 1988; Li and Reynolds 1993) that measured the adjacency of land cover types, with large values of C indicating a clumped landscape. We compared the position of different land-cover types by looking at the percentage of a 100 m stream buffer that was in forest (cf., Omernik and others 1981).

Of particular importance was the relationship between these parameters of landscape structure and relative nutrient storage in the basins. Scattergrams between parameters of landscape structure and storage ratios of basins were used to identify the direction and form of the relationships. The Pearson product-moment correlation coefficient was calculated (Hammond and McCullagh 1978) to determine the degree (r) and significance of correlations (prob. <0.05) between each parameter of landscape structure and components of the budget.

RESULTS

Water Balance

Mean annual precipitation measured at the Miami Conservancy District (MCD) weather station from 1945 to 1993 was 101.9 cm, whereas total precipitation measured at the Ecology Research station during 1994 was 80.5 cm (83.1 cm at MCD), significantly below the long-term average (Fig. 3). With the exception of April and November, all months were drier than normal. Two large April storms contributed 21% of the year's precipitation. Except for a significant event the last week in June, precipitation values were low through the study period. PET during 1994 was 70.1 cm, or slightly higher than the long-term average of 69.5 cm. The total moisture deficit was larger and lasted a month longer for 1994 than for the long-term average (Fig. 3). The long-term budget yields 31.0 cm of runoff, while the 1994 calculated budget yields only 14.0 cm. Runoff derived from a provisional rating curve at the permanent gauging station on Marshall's Branch in 1994 was about 25.0 cm (0.2566 m), or also below the long-term average. Due to the warm and unusually dry weather, no runoff reached streams in the smaller sub-basins from August till the end of the sampling period in October. Some water may have moved through the basins underground, but even the gauging station on Marshall's Branch recorded zero flow during the period between mid-August and late-November.

Nutrient Budgets

Nitrogen. The nitrogen budget was based on nitrogen unit loads (kg/ha) for the seven basins during the study period (Table 1). Nitrogen deposited by precipitation in the watershed was 5.6 kg/ha. Livestock input was 5.0 kg/ha for grazed Midwestern pasture land (see Beaulac and Reckhow 1982). Local farm surveys documented fertilizer inputs of 183.1 kg/ha for corn and none for soybeans (Mull and Ramsey 1994). Crop harvest outputs equaled 135.0 kg/ha of corn and 10.0 kg/ha of soybeans, considering both crop utilization and soybean nitrogen fixation (Logan 1990; Mull and Ramsey 1994).

Average concentrations of soluble nitrate and total

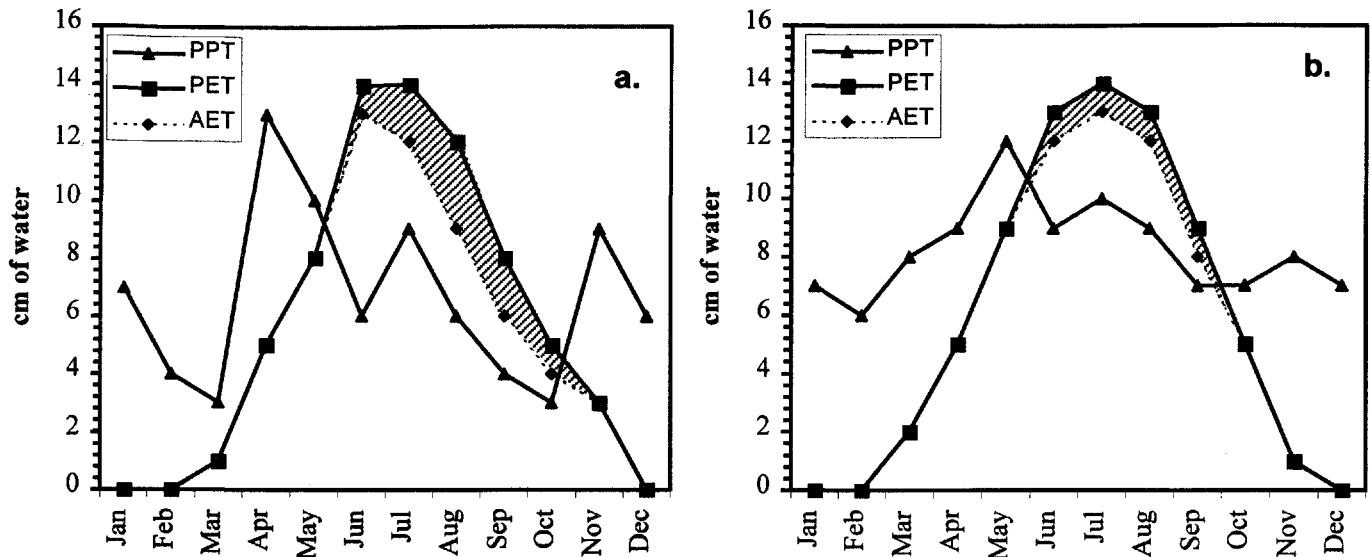


FIGURE 3. Comparison between the calculated water budgets for: a) 1994; and b) long-term averages (1945-1993), using climatological data from Oxford, OH. Times and amounts of moisture deficit are shaded on the graphs. Shown on the graph are the relationships between precipitation (PPT), potential evapotranspiration (PET), and actual evapotranspiration (AET).

nitrogen output from each study basin were calculated from a maximum of 11 weekly stream samples and four storm events. Soluble nitrate concentrations ranged from 3.3 mg/l in Basin 1 to above 10.0 mg/l in Basins 2 and 4. Basins 2, 4, 7, and 9 exceeded reported values for mean nitrate concentrations in tributaries of Lake Erie (2.3–5.1

mg/l; Baker 1993). The average concentration of total nitrogen in the sub basins ranged from 4.7 mg/l in Basin 11 to 10.9 mg/l in Basin 2. Stream samples for all basins had at least 50% of total nitrogen arriving in soluble form. Stream unit loads for total nitrogen ranged from 12.1 kg/ha for Basin 11 to 28.1 kg/ha for Basin 2 (Table 1).

TABLE 1

Nitrogen budget calculations for the 1994 growing season in the study basins of Marshall's Branch watershed.

Basin	Basin Areas ha	Stream unit load kg /ha	Inputs			Outputs		Storage	
			Deposition ^a	Livestock ^b	Cropland ^c kg	Cropland ^d	Stream ^e	kg/ha ^f	IO ratio ^g
1	194.8	17.1	1098.4	74.1	18185.6	14070.4	3330.2	10.0	1.11
2	70.8	28.1	399.0	7.2	7180.6	5555.7	1988.0	0.6	1.01
4	103.2	25.7	582.0	23.9	10302.3	7971.0	2651.9	2.8	1.03
6	366	14.9	2064.6	114.6	33261.5	25734.8	5454.3	11.6	1.14
7	45.3	25.2	255.4	0.0	4858.1	3758.8	1141.3	4.7	1.04
9	186.4	23.7	1051.1	72.4	17166.3	13281.8	4416.8	3.2	1.03
11	108.6	12.1	612.5	17.0	5966.5	4616.3	1314.0	6.1	1.11
							Mean storage =	5.6	1.07
							Std Deviation =	4.0	0.05
Regional unit loads									
							kgN/ha		
			Precipitation deposition	=	5.6				
			Livestock	=	5.0				
			Fertilizer, corn	=	183.1				
			Fertilizer, soybean	=	0.0				
			Harvest, corn	=	135.0				
			Harvest, soybean	=	10.0				

^aPrecipitation deposition = regional unit load * total basin area

^bLivestock = regional unit load * total pasture area

^cCropland input = (fertilizer for corn * corn crop area) + (fertilizer for soybeans * soybean crop area)

^dCropland output = (harvested corn * corn crop area) + (harvested soybeans * soybean crop area)

^eStream output = stream unit load * total basin area

^fTotal storage = (Inputs-Outputs)/total basin area

^gIO ratio = Inputs/Outputs

The storage ratio (IO), calculated as the sum of total inputs divided by the sum of total outputs, ranged from 1.01 for Basin 2 to 1.14 for Basin 6. All basins stored nitrogen during the 1994 growing season. However, Basins 1, 6, and 11 are greater than 1.10, and Basins 2, 4, 7, and 9 are below 1.05, above and below the mean of 1.07, respectively. Basins 1, 6, and 11 stored proportionally more nitrogen than was lost during the study, and Basins 1 and 6 stored much more nitrogen (Table 1). Although these differences seem small and nonsignificant, they can translate to large amounts of nitrogen when basin areas are considered in the calculation. For instance, Basin 2, which had low storage (0.6 kg/ha) and a lower ratio between inputs and outputs (1.01) than Basin 6 (11.6 kg/ha, IO = 1.14), stored only 43.1 kg of nitrogen during the study period in comparison with the 4251.6 kg stored in the much larger Basin 6.

Phosphorus. Total phosphorus unit loads, the sum of soluble reactive phosphorus and particulate phosphorus, were used to calculate the phosphorus budget for the growing season in 1994 (Table 2). Phosphorus deposition by precipitation in the watershed equaled 0.12 kg/ha (NADP/NTN 1995). A livestock coefficient of 1.5 kg/ha was derived from records for grazed pasture in the Midwest (Bealac and Reckhow 1982). Local farm surveys reported fertilizer inputs of 21.9 kg/ha for corn and 5.0 kg/ha for soybeans, and crop exports of 12.7 kg/ha for corn and 9.7 kg/ha for soybeans (Mull and Ramsey 1994; cf.,

Peterjohn and Correll 1984; Lowrance 1992; Burt 1993).

Stream unit loads for total phosphorus ranged from 0.3 to 1.6 kg/ha (Table 2). Calculated from the stream samples, the unit loads of soluble reactive phosphorus (SRP) ranged from 0.1 kg/ha in Basin 6 to 1.4 kg/ha in Basin 9, and unit loads of particulate phosphorus (PP) ranged from 18.0 µg/l in Basin 6 to 175.2 µg/l in Basin 1. Except for Basin 9, all of the study basins are within or below averages for SRP (0.6-0.9 kg/ha) and PP (0.3-0.4 kg/ha, Logan 1990). Reported phosphorus unit loads from agricultural watersheds in northern Ohio range from 1.1-1.4 kg/ha (Baker 1993). Basins 9 and 1 are above 1.0 kg/ha, whereas the other five basins are below 0.7 kg/ha.

Storage (IO) ratios ranged from 1.15 for Basin 9 to 1.29 for Basin 7 (Table 2). All basins stored phosphorus during the study period but varied in their relative ratios and total amounts based on basin size. Basin 9 had notably the lowest storage ratio (1.25). Basin 11 had a slightly higher IO ratio (1.28) but its unit storage was comparable with Basin 9, whereas Basin 7 showed the highest unit storage (3.4 kg/ha) and the highest storage ratio (1.29) and Basin 6 had the highest storage for the basin (1025 kg). Small comparative differences in the storage ratios can affect significant differences in the storage amounts among the stream basins.

Landscape Analyses

All the basins were dominated by cropland, but they differed in the structure of the other land uses. Land

TABLE 2

Phosphorus budget calculations for the 1994 growing season in the study basins of Marshall's Branch watershed

Basin	Basin Areas ha	Stream unit load kg /ha	Inputs			Outputs		Storage		
			Deposition ^a	Livestock ^b	Cropland ^c kg	Cropland ^d	Stream ^e	kg/ha ^f	IO ratio ^g	
1	194.8	1.0	23.4	22.2	2506.2	1903.6	194.7	2.3	1.22	
2	70.8	0.7	8.5	2.2	989.6	751.7	49.5	2.8	1.25	
4	103.2	0.6	12.4	7.2	1419.8	1078.4	61.9	2.9	1.26	
6	366	0.4	43.9	34.4	4583.8	3481.8	146.4	2.8	1.28	
7	45.3	0.3	5.4	0.0	669.5	508.5	13.6	3.4	1.29	
9	186.4	1.6	22.4	21.7	2365.7	1796.9	298.2	1.7	1.15	
11	108.6	0.3	13.0	5.1	822.2	624.6	32.6	1.7	1.28	
								Mean storage =	2.5	1.25
								Std Deviation =	0.6	0.05
Regional unit loads										
						kgP/ha				
			Precipitation deposition	=		0.1				
			Livestock	=		1.5				
			Fertilizer, corn	=		21.9				
			Fertilizer, soybean	=		5.0				
			Harvest, corn	=		12.7				
			Harvest, soybean	=		9.7				

^aPrecipitation deposition = regional unit load * total basin area

^bLivestock = regional unit load * total pasture area

^cCropland input = (fertilizer for corn * corn crop area) + (fertilizer for soybeans * soybean crop area)

^dCropland output = (harvested corn * corn crop area) + (harvested soybeans * soybean crop area)

^eStream output = stream unit load * total basin area

^fTotal storage = (Inputs-Outputs)/total basin area

^gIO ratio = Inputs/Outputs

percentages in forest ranged from 1.8% to less than 10% in six of the basins, and up to 45.4% in Basin 11. All basins except 6 and 11 were 5% or less forested. Proportions of pasture were below 8% for all basins and ranged from 0% in Basins 7 and 11 to 7.8% in Basin 9. Residential land, though below 4% for all the study basins, varied from 0.5% to 3.5%. Shrub/brush and other land uses were below 2% for all basins.

All basins had less than 45 total patches of different land-cover types (Table 3). Basin 6 had 44 patches, but three of the basins had fewer than five patches. Six of the seven basins had less than 12 patches/ha, but Basin 2 had a higher patch density with 21 patches/ha. Scaled contagion (C) values were above 0.8, indicating a dominance by large, contiguous patches. While this may be a desirable situation in natural landscapes, cropland, a disturbed patch type, dominated the large contiguous landscapes of all the basins except Basin 11.

Proportions of forest area in the stream buffers give an estimate of the extent of riparian habitat in each basin (Table 3). Forest proportions ranged from 0% in Basin 2 to 87% in Basin 11. Basins 1, 6, and 11 are above 25% forest in the buffer, while the other four basins are below 15% forested.

We hypothesized that proportions, configuration, and position of uncultivated (forest) land near streams would have significant relationships with the storage capacity of the basins. The storage (IO ratios) of nitrogen in the basins showed highest correlations with the percentage of 100 m stream buffers that were in forest ($r = 0.69$; prob. <0.01). A positive but non-significant correlation also occurred with the proportion of forest in the basins ($r = 0.49$; prob. >0.05). When Basin 11, a basin with a much higher percentage of forest, was omitted from these analyses, the correlation between nitrogen storage and forest in the buffer was much stronger ($r = 0.91$; prob. <0.01) and the correlation was higher and significant with forest cover ($r = 0.85$, prob.

<0.01). Scattergrams (Fig. 4a,b) showed that the much higher forest cover of Basin 11 did not result in much higher storage, a finding that may be partially attributable to its higher slopes and greater relief ratio. For the other basins, changes in storage were notable with very small increases in forest cover.

Phosphorus storage (IO ratios) had positive but non-significant correlations with the percentage of forest cover ($r = 0.29$; prob. >0.05) and its percentage within a 100 m buffer ($r = 0.30$; prob. >0.05). In contrast, high and significant correlations occurred with the percentage of pasture ($r = -0.68$; prob. <0.05) and with the percentage of residential land ($r = -0.90$; prob. <0.01). An increase in

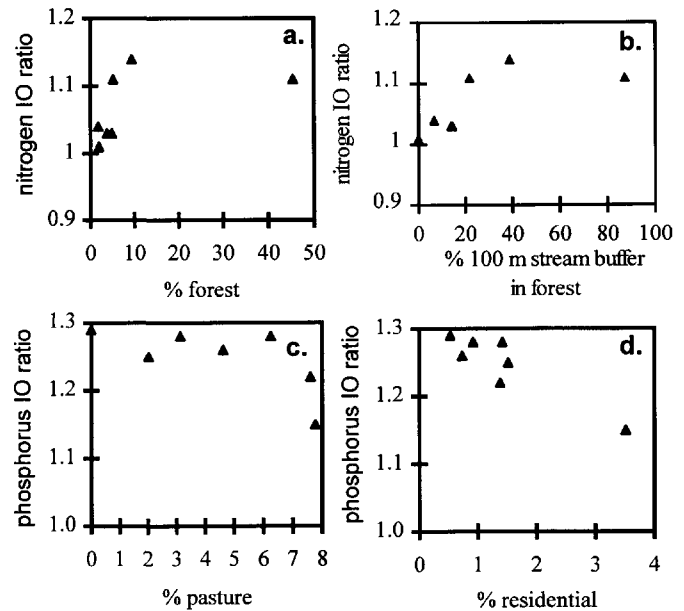


FIGURE 4. Scattergrams showing significant correlations between parameters of landscape structure and the nutrient storage (IO ratios) for the seven study basins.

TABLE 3

Comparative landscape analysis of the seven study basins in the Marshall's Branch watershed based on land-cover proportions, the configuration of land-cover types, and the position of forest along stream corridors.

Landscape Attribute	Basin 1	Basin 2	Basin 4	Basin 6	Basin 7	Basin 9	Basin 11
Land-cover Proportions							
% cropland	85.0	92.4	90.9	82.7	97.6	83.8	50.0
% forest	5.2	1.9	3.8	9.4	1.8	4.9	45.4
% pasture	7.6	2.0	4.6	6.3	0.0	7.8	3.1
% residential	1.4	1.5	0.7	0.9	0.5	3.5	1.4
Land-cover Configuration							
# patches	17	15	7	44	4	21	6
patch density (#/ha)	9	21	7	12	9	11	6
contagion index	0.923	0.895	0.912	0.919	0.954	0.886	0.933
Land-cover Position							
% of a 100 m stream buffer that is in forest cover	21.8	0.00	14.1	39	6.4	14.3	87.0

pasture above 6% and small increases in residential land were related with a decline in the IO of phosphorus (Fig. 4c,d). For pasture, the relationship is probably best explained by the correspondence between pasture land and inputs from livestock (Table 2). Also the contagion index, counterintuitively, showed a significant positive relationship with phosphorus storage ($r = 0.73$; prob. <0.05); more clumped landscapes had greater storage. These findings are confounded by the clumped occurrences of cultivated land in all basins and the clumped occurrence of forest in Basin 11.

DISCUSSION

Flows of excess nutrients in agricultural landscapes can cause water quality problems in streams draining those regions. When coupled with analyses of landscape structure, nutrient budgets highlight important nutrient sources and sinks. In application, potential management techniques can then be developed to ameliorate the effects of excess nutrient exports. Our study focuses on the calculation of nutrient budgets for a single growing season in seven first-order basins contained in a 13 km² watershed. Nutrient flows were susceptible to fluctuations in the seasonal climate conditions; sufficient water must be available to transport the nutrients through the landscape. Precipitation values in 1994 were much lower than average, resulting in a longer and deeper moisture deficit. Some of the streams were dry on sample days and all of the streams were dry by August, effectively ending the transport of nutrients for the growing season.

A drier than normal year can affect major nutrient export pathways such as stream outflow. The total runoff from Marshall's Branch watershed for 1994 was 25.0 cm, which is less than the expected runoff of 31.0 cm calculated from long-term averages measured at a weather station located six miles south of the watershed. Less runoff from the basins reduces the overall movement of nutrients through the landscape, thereby exaggerating the storage potential of the study basins. While mean conditions may not be reflected and should not be interpreted from our sample, comparative budget calculations and the relationships between land use and storage ratios explored by the study should remain valid.

Nutrient Budgets

The nutrient budgets calculated for the seven first-order basins did show a range of inputs and outputs from the Marshall's Branch watershed. Basins 2, 4, and 7 had nitrate concentrations above 10 mg/l, the safe water standard set by the US EPA. However, the nutrient export rates for the sampled growing season are lower than annual rates for Marshall's Branch (nitrate at 20.53 kg N/ha/yr; Vanni and others 2001) and those reported for other agricultural watersheds. For example, Lowrance (1992) reported total nitrogen exports of 39.1 kg N/ha/yr, and Kesner and Meentemeyer (1989) reported even higher values, with an annual average export of 52.9 kg N/ha. Both studies conducted on the coastal plain of Georgia investigated watersheds with sandy soils and large subsurface runoff over longer term periods. In fact, the majority of nitrogen exported from these water-

sheds was in subsurface flow, a phenomenon that was also observed in loess soils in Iowa agricultural land (Burwell and others 1977) and predicted for the loess soils of southwest Ohio. Subsurface nutrient export was not measured separately from surface flow in Marshall's Branch watershed, and may have been particularly affected by the low flow conditions of the 1994 growing season.

Burwell and others (1977) investigated the effect of cropping practices on nitrogen export from corn-cropped watersheds in Iowa. Over the six-year study period, conventionally tilled watersheds exported an average of 28.1 kg N/ha/yr. In Marshall's Branch, Basins 2, 4, 7, and 9, which are most heavily dominated by cropland, have similar export values. When the Iowa watersheds were rotated through pasture and mulch tilled corn, average nitrogen export was 14.1 kg N/ha/yr. This value is similar to Basins 1, 6, and 11, the less cultivated basins in the watershed. Uncultivated lands reduce nutrient export similarly to changes in tillage practices.

According to the phosphorus storage ratios calculated for the growing season in 1994, the basins each store around 20% of the phosphorus input to the system. The high rate of phosphorus storage in the basins may be exaggerated for a single growing season. Since a proportion of total phosphorus is sediment bound, there is significant delay between application and its export. Much of the phosphorus applied may remain in the soils until significant runoff transports the sediment downstream (e.g., the following spring). In studies of sediment redistribution in riparian zones, most sediment is deposited within 100 m of the field from which it originated (Cooper and others 1987). Concentrations of phosphorus are greater in these deposits than in the fields, representing 20- to 25-year soil stores (Cooper and Gilliam 1987). Based on multi-year data collected at the gauging station on Marshall's Branch, there is a significant positive relationship between discharge and particulate phosphorus concentration (e.g., Vanni and others 2001). Therefore particulate phosphorus concentration is a more significant proportion of the total phosphorus load in a wetter year with higher annual discharge. In a year with reduced runoff, such as 1994, the concentration of phosphorus and therefore the total load of phosphorus transported may be reduced, resulting in the calculation of higher annual storage.

Relationships Between Nutrient Flows and Landscape Structure

The study documents relationships that exist between landscape structure and nutrient storage. These trends appear to confirm other research that has correlated land use proportions and spatial pattern with water quality measures (Hunsaker and Levine 1995). Nitrogen storage was significantly related to the amount of land in forest, especially within the 100 m stream buffers. In these basins, secondary growth forest generally replaces cropland removed from cultivation, and therefore less fertilizer is applied in these basins. Forest within the 100 m stream buffers includes riparian forest. These areas can capture and store nitrogen in woody

vegetation (Lowrance and others 1984), resulting in lower in-stream concentrations of nitrogen, regardless of input levels.

Forest area differences among six of the seven basins are small, but relate to large differences in the nitrogen storage capacities of the basins. For example, the actual area of the 100 m stream buffers in the seven basins ranged from 16% to 27.8% of the total basin areas. Forest proportions in the buffers ranged from 0% to 87%. Therefore, the forested buffer cover accounts for 0% in Basin 2 to 16% in Basin 11 of the total basin areas. The impact small changes in forest cover can have on nitrogen storage is demonstrated by comparing Basins 2 and 6. The nitrogen storage rates (kg stored per ha of total basin area) in the basins are 0.6 kg/ha for Basin 2 (0% forested buffer) and 11.6 kg/ha for Basin 6 (39% forested buffer). The difference in forested buffer is 6.2% of total basin area, but the difference in storage rates is 11.0 kg/ha. Based on the areas of the two basins, the actual load of nitrogen stored in Basin 6 (4252 kg) is a 100-fold difference from that stored in Basin 2. If changes in the land use of the basins result in a net export of nutrients, it is apparent that the subsequent load of nitrogen downstream would be large. It is easy to see that in larger basins of hundreds of km, small increases in forest, especially when they occur along streams, could promote nitrogen storage on the order of metric tons of nitrogen stored. Although some would probably reach the stream from groundwater flow, a large portion could be used to promote forest growth and long-term storage in woody biomass (Lowrance and others 1984).

Phosphorus storage appears to be more related negatively with the area percentages of pasture and residential lands, than positively with forest cover. Based on field observations, most of the pasture land in the study basins was actively grazed in 1994. During grazing, cows trample vegetation, compact soils, and disturb the nutrient storage capacity of the land. They also eat vegetation and produce manure, essentially releasing phosphorus as an output. Pastures, especially when they occur along streams, can have a major impact on water quality.

As the percentage of residential area increased, phosphorus concentrations increased, corresponding with a decrease in phosphorus storage. In the study basins, residential land use consists mostly of farmsteads. These rural residences use septic tank systems to treat sewage. Up to 85% of phosphorus in septic tanks is in soluble form, although most of this percentage becomes bound to the soil if it leaks from the tank (Canter and Knox 1985). However, the remaining soluble proportion may return to surface waters through interflow, increasing the in-stream concentrations of phosphorus. The Midwest and Ohio agricultural regions are experiencing an increase in the number of residences built on converted farmland, and it is likely that our values based on 1989 land-cover data are low estimates. Models of urbanization in agricultural lands predict increases in phosphorus concentrations (e.g., Osborne and Wiley 1988). Similar results could be expected in Marshall's Branch with an increase in rural residences.

While these trends have implications for land use

management in the Marshall's Branch watershed, the processes of nutrient flows and storage can be expected to vary over large temporal and spatial scales. Longer-term investigations are necessary to account for the effects of variable climatic factors on total nutrient outputs and the relative amounts of nutrient outputs from the basins. Larger-scale research is needed to isolate the effects of environmental variables, such as soil type and slope on the ability of forest buffers to reduce nutrient flows. Our study, however, does give a strong indication of significant relationships between landscape structure and nutrient budgets, and most importantly shows that small changes in land cover can have profound effects on nutrient flows. If further research confirms or strengthens these trends, our conclusions can lead to more efficient conservation practices in agricultural landscapes.

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