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Riparian Forests as Nutrient Filters in Agricultural Watersheds

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Riparian (streamside) vegetation may help control transport of sediments and chemicals to stream channels. Studies of a coastal plain agricultural watershed showed that riparian forest ecosystems are excellent nutrient sinks and buffer the nutrient discharge from surrounding agroecosystems. Nutrient uptake and removal by soil and vegetation in the riparian forest ecosystem prevented outputs from agricultural uplands from reaching the stream channel. The riparian ecosystem can apparently serve as both a short- and long-term nutrient filter and sink if trees are harvested periodically to ensure a net uptake of nutrients. *(Accepted for publication 28 November 1983)*

Agricultural landscapes are often a mosaic of intensively and extensively managed lands. Often, the less-managed portions of agricultural watersheds are poorly drained wetlands adjacent to the watercourses that drain the basin. Although the economic and environmental costs of cultivating these areas are usually high, pressure to create larger fields often brings these marginal lands into production. In many parts of the southeastern US coastal plain, land use on agricultural watersheds consists of row crops in well-drained uplands and native bottomland hardwood forests in streamside (riparian) areas.

Studies of the Little River watershed in the Tifton upland subprovince of the Georgia coastal plain showed that, despite large fertilizer inputs to row-crop fields, streamflow outputs of NO_3-N from the watershed were less than inputs in precipitation (Asmussen et al. 1979). We hypothesized that riparian ecosystems filter nutrients and help maintain water quality on agricultural watersheds. To test this hypothesis we studied nutrient cycling using two approaches: we determined the annual flux of N, P, Ca, Mg, K, and Cl to and from the riparian ecosystem and the net annual uptake of N, P, Ca, Mg, and K into aboveground woody vegetation in the forest.

Water and nutrient movements on agricultural watersheds are controlled by a combination of biological and physical factors. Terraces, channelization, and artificial drainage are commonly used to control the physical factors. If riparian forests are nutrient filters or buffers in agricultural watersheds, they play a biologically important role and should be included in designs for watershed management.

Previous studies presented conflicting conclusions on the effect of riparian vegetation on stream water quality. Karr and Schlosser (1978) speculated that streamside vegetation may reduce streamflow nutrient loads via shading and streambank stabilization. Schlosser and Karr (1981) also emphasized that maintenance of riparian vegetation was necessary to improve water quality in agricultural watersheds. Channelized coastal plain streams had higher nutrient concentrations than unchannelized streams, due at least partially to the loss of contact between flowing water and the riparian swamp forest (Kuenzler et al. 1977). Omernik et al. (1981) hypothesized that mature riparian forests are not nutrient filters, since no net annual uptake would take place. On the other hand, a study of riparian peatlands of a forested watershed in Minnesota revealed that 36–60% of all annual nutrient inputs were retained in the streamside zone (Verry and Timmons 1982).

An understanding of nutrient filtering by riparian ecosystems should be based on studies of nutrient cycling and of nutrient flux across ecosystem boundaries. High flux of nutrients in streamside areas may be due to floodwaters from rivers (Brinson et al. 1980); in agricultural watersheds streamside nutrient enrichment may be caused by inputs from fields. Nutrient budgets for the riparian zone of an entire agricultural watershed, developed to directly assess its nutrient filtering capacity, have not previously been developed.

WATERSHED N STUDY

We studied watershed N, a subwatershed of Little River (Figure 1). It is 1568 ha with 30% riparian forest; 41% row crops; 13% pasture; and 16% roads, residences, fallow land, and other uses. Crops include corn, peanuts, soybeans, tobacco, sorghum, and vegetables. Annual inputs of nutrients in fertilizer and lime to row crops and pastures in the uplands are high. Dominant tree species in the riparian forest are *Nyssa sylvatica* (black gum), *Liriodendron tulipifera* (tulip tree), *Magnolia virginiana* (sweet bay), *Acer rubrum* (red maple), and *Quercus nigra* (water oak) (Fail 1983). Trees are periodically harvested for timber and fuelwood. Watershed N has a relatively intact riparian zone (Figure 2), and all waterborne nutrient outputs from upland fields must pass through this zone before they reach the stream channel. All nutrients in streamflow either originate in or pass through the riparian ecosystem. Surface soils of the watershed are underlain by Miocene sediments (Hawthorne formation), which form an aquiclude, a porous but almost impermeable layer that confines a shallow aquifer. Much of the 1203 mm of annual precipitation infiltrates and moves laterally to the stream channel in a shallow aquifer above the aquiclude. Plot studies showed that 80% of total runoff and 99% of NO_3-N was moved from fields in subsurface flow (Jackson et al. 1973).

Inputs, outputs, and vegetation storages of N, P, K, Ca, Mg, and Cl in the riparian ecosystem were measured from 1979 to 1981. A broad-crested v-notch weir was installed at the watershed outlet in 1971 to measure streamflow vol-

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umes. Streamflow nutrient concentrations were determined on filtered samples collected at the weir every 12 hours. Nutrient loads in streamflow were estimated by integrating nutrient concentrations with streamflow volumes. Precipitation loads were determined by integrating precipitation volumes with nutrient concentrations collected at three locations in the Little River Watershed. Waterborne nutrient concentrations in subsurface flow from upland fields, pastures, and forests were estimated using 37 wells arranged along nine transects (Figure 1) leading from the upland/riparian interface to the stream channel (Lowrance et al. 1983). Average monthly concentrations, weighted for land use at the interface, were applied to estimated monthly water surpluses (Thornthwaite and Mather 1957) to determine annual loads.

Outputs of N in denitrification and inputs in nonsymbiotic N-fixation were estimated on six transects using acetylene inhibition and acetylene reduction techniques, respectively (Hendrickson 1981). Soil cores were collected monthly and incubated in the field for 24 hours after acetylene was injected into the cylinder containing the core. Symbiotic N-fixation by *Myrica cerifera* (wax myrtle) was estimated from forest composition data of Fail (1983), and values reported from similar forests (Permar and Fisher 1983). Fail (1983) estimated annual increments of nutrient storage in aboveground boles from nutrient concentrations in woody plant tissue, community species composition, biomass estimates, and forest age based on increment borings. Measurement of inputs, outputs, and storages of nutrients in the riparian forest ecosystem are schematically illustrated in Figure 1.

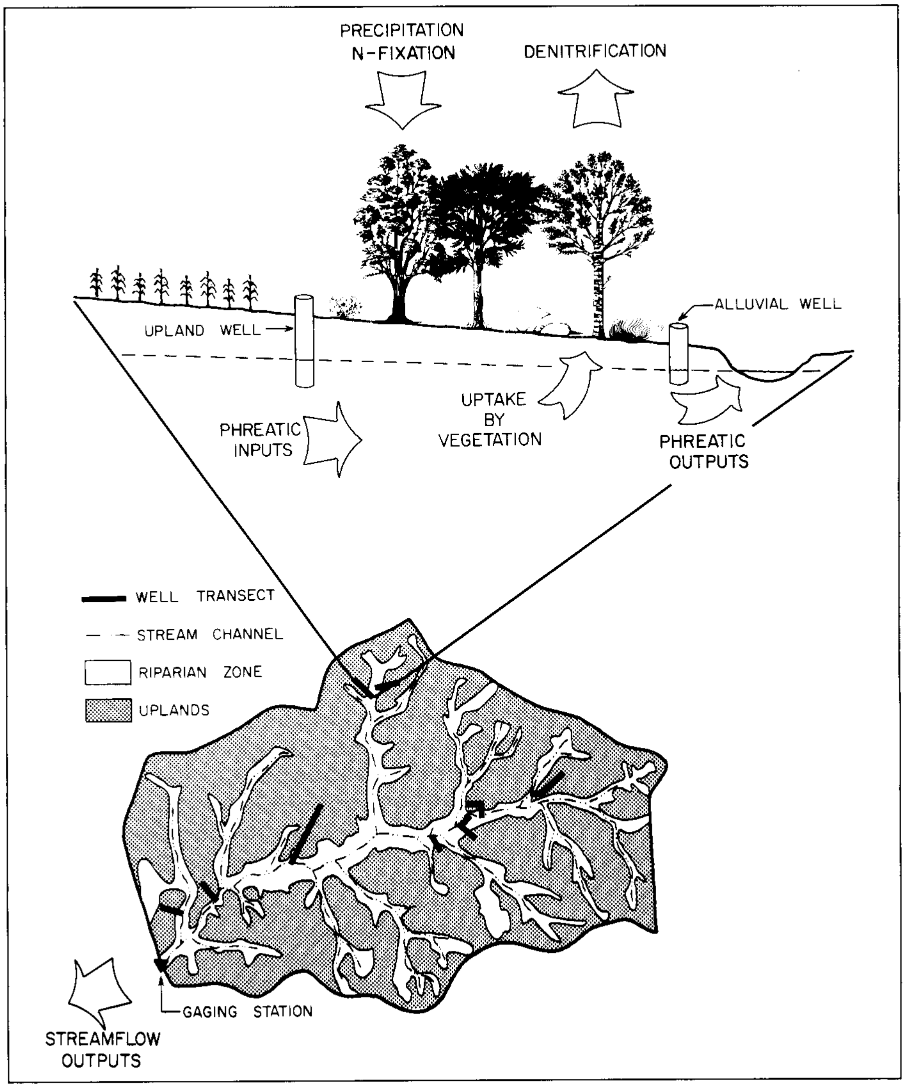

Figure 1. Map of watershed N showing location of transects and riparian forests and a schematic illustration of the measurement of inputs, outputs, and storages of nutrients.

NUTRIENT BUDGETS FOR THE RIPARIAN SYSTEM

Nutrient inputs, outputs, and accruals in woody vegetation are given in Table 1. Waterborne inputs exceeded streamflow outputs for all elements. The order of net nutrient retention (precipitation + subsurface − streamflow, all units kg/ha) was N>Ca>Cl>Mg>P>K. Percentages of input retained ([retention/input] × 100) were N-68%; Ca-39%; P-30%; Mg-23%; Cl-7%; and K-6%. Thus, N had a very high retention rate; Ca, P, and Mg had moderate rates; and Cl and K were essentially balanced. Based solely on these annual differences in input and output, the riparian ecosystem was a short-term filter for N, Ca, P, and Mg from upland areas.

Nitrogen is unique among these nutrients, since the global N reservoir is in the atmosphere. Gaseous flux of N across ecosystem boundaries can take place through diffusion from leaf surfaces, N fixation, NH_4-N volatilization from soils, denitrification, and production of N_2O during nitrification. Gaseous losses were apparently more important than gaseous inputs. N-fixation to the riparian ecosystem was less than either subsurface or precipitation inputs, but denitrification losses of N were over twice streamflow N loads. Soils of the riparian ecosystem presented ideal conditions for denitrification: high organic matter from input of forest litter; seasonal waterlogging; and large inputs of NO_3-N in subsurface flow. Dentrification outputs alone were enough to remove all the N inputs from upland fields to the riparian zone (Table 1).

Estimated rates of accrual in aboveground vegetation followed a pattern similar to that for net retention with N>Ca>K>Mg>P (Table 1). Nutrient accrual in vegetation exceeded the net difference between input and output for all elements. Vegetation accrual of nitrogen exceeded the total input from precipitation and subsurface flow. Since the average age of the forest ranges from 22.0 to 35.2 years (Fail 1983), uptake in boles is medium-term storage that becomes output when trees are harvested. The selective cutting of mature trees for timber or fuelwood will maintain the net annual nutrient uptake by vegetation.

FACTORS AFFECTING NUTRIENT BUDGETS

The balance column in Table 1, (input − [output + storage]) shows that outputs and storages accounted for more of each element than entered the riparian ecosystem. Therefore, annual nutrient budgets are unbalanced. We hypothesize two possible sources of these unaccounted-for nutrients: annual nutrient movement in surface runoff from uplands and nutrient storage in sediment and buried vegetation during the 100–125 years since the uplands were originally cleared and cultivated.

Total annual inputs from uplands were underestimated because surface nutrient movement was not included. Estimates on watershed N indicated that 80–96% of the water movement from uplands to the riparian ecosystem occurred as subsurface flow (Lowrance et al. 1983). Therefore, relatively small volumes of surface runoff probably transported relatively small nutrient loads. Nutrients carried into the riparian ecosystem in surface runoff can either be retained through sediment deposition and adsorption of dissolved nutrients, or the nutrients can be carried into the stream channel system and end up as output at the weir. Since inputs from surface runoff were not included, the budgets in Table 1 are overestimates of nutrient deficits and would be more nearly balanced if surface inputs had been included.

Observations in the riparian zone indicate that 40–60 cm of recent sediment is often found above original soil surfaces. These sediments have been deposited in bottomland areas since original clearing of the upland forest took place approximately 100–125 years ago. Large quantities of buried woody vegetation were encountered below 40–50 cm during root studies (Hamzah 1983) at most transect sites. This buried vegetation was apparently deposited within the last century under changing hydrologic and soil conditions in the riparian ecosystem. We hypothesize that annual nutrient budgets for the riparian ecosystem do not balance due to these storages of nutrients in sediment and dead vegetation over a long period of time. The annual increment of nutrient mineralization or release from this long-term storage would be available for uptake by vegetation and microorganisms present today. Once these stored nutrients are released, they are also available for transport to the stream channel. Nutrient budgets for the riparian zone should balance over longer periods of time (decades and centuries) due to this long-term storage of nutrients and the annual increment of nutrient release.

Table 1. Nutrient inputs, outputs, storages, and balances for the riparian zone of an agricultural watershed. All units are kg/yr/ha of riparian ecosystem.

	Inputs			Outputs			
	Precipitation	Subsurface	N fixation	Streamflow	Denitrification	Aboveground storage	Balance Input-(output + storage)
N	12.2	29.0	10.6	13.0	31.5	51.8	−44.5
P	3.5	2.1	—	3.9	—	3.8	−2.1
Ca	5.2	47.4	—	31.8	—	40.3	−18.5
Mg	1.4	18.1	—	15.0	—	6.1	−1.6
K	3.9	19.5	—	22.2	—	18.6	−17.4
Cl	21.4	83.5	—	97.0	—	—	7.9

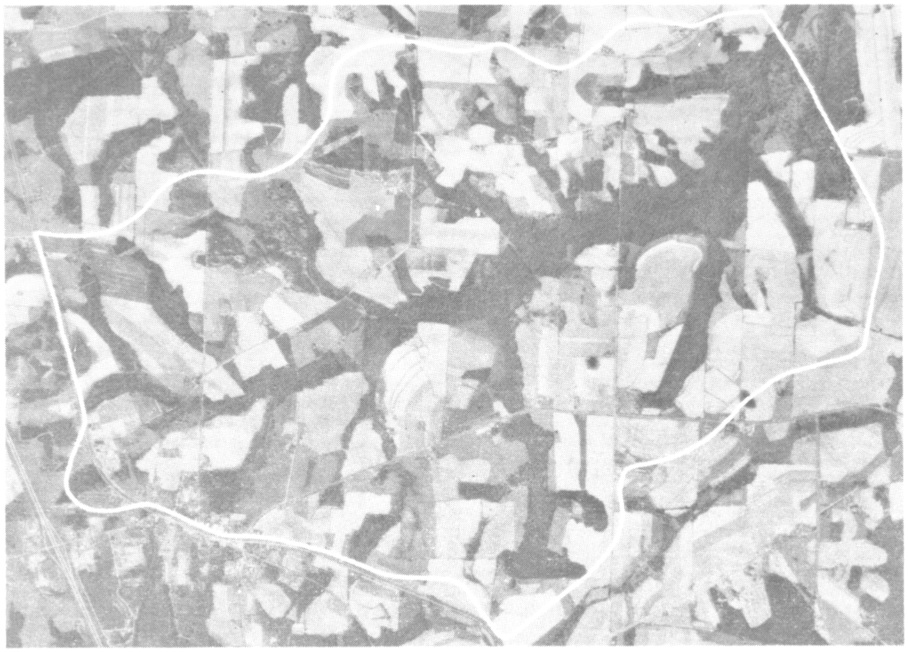

Figure 2. Aerial composite photograph of watershed N showing the distribution of fields (lighter areas) and riparian forest (darker areas).

IMPLICATIONS FOR WATERSHED MANAGEMENT

Much agricultural development in the southeast is occurring at the expense of bottomland hardwood forests. From 1951 to 1971, 67,000 ha of bottomland hardwoods were cleared in a 22-county area of south Georgia (USFS 1952, 1971). From 1973–1976, more than 89,000 ha of Georgia coastal plain was brought under cultivation; 57% of this new cropland was previously forested (White et al. 1980).

Even though large areas of bottomland forest are being converted to cropland, water quality in coastal plain agricultural watersheds is still generally good compared to water quality standards, and agricultural watersheds generally have better water quality than more urbanized watersheds (Asmussen et al. 1975). Based on the results of this study, good water quality for agricultural watersheds depends largely on nutrient uptake and removal in the riparian ecosystem. Removal of the riparian forest, often accompanied by tile drainage, would tend to contribute to higher nutrient loads in streams and lower water quality through: loss of nutrient uptake and storage by woody vegetation. Changes in mineralization rates and denitrification capacity due to increased aeration, loss of capacity for removal of sediment from flood waters and runoff, and increased nutrient runoff from riparian areas due to fertilizer application to streamside fields would also increase nutrient loads. Maintenance and proper management of riparian ecosystems in the coastal plain are essential to avoid degradation of water quality due to increased nutrient loss from agricultural watersheds. Proper streamside forest management requires both periodic harvest of trees to maintain nutrient uptake and minimum disturbance of soil and drainage conditions. Future research may lead to the use of more economically valuable perennial vegetation in some streamside areas, but we must require that new management techniques maintain the basic nutrient filter role of riparian ecosystems.

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REFERENCES CITED

Asmussen, L. E., J. M. Sheridan, and H. D. Allison. 1975. Water quality inventory of the southern Coastal Plain and Atlantic Coast Flatwoods of Georgia. *US Dep. Agric. Agric. Res. Serv. ARS (Ser)* 49.

Asmussen, L. E., J. M. Sheridan, and C. V. Booram, Jr. 1979. Nutrient movement in streamflow from agricultural watersheds in the Georgia Coastal Plain. *Trans. Am. Soc. Agric. Eng.* 22: 809–815, 821.

Brinson, M. H., H. S. Bradshaw, R. N. Holmes, and J. B. Elkins, Jr. 1980. Litterfall, stemflow, and throughfall nutrient fluxes in an alluvial swamp forest. *Ecology* 61: 827–835.

Fail, J. L., Jr. 1983. Community structure, biomass, and nutrients in a swamp hardwood forest. Ph.D. Dissertation, University of Georgia, Athens, GA.

Hamzah, N. M. 1983. Root production, decomposition, and nutrient uptake in a bottomland hardwood forest. Ph.D. Dissertation, University of Georgia, Athens, GA.

Hendrickson, O. Q., Jr. 1981. Flux of nitrogen and carbon gases in bottomland soils of an agricultural watershed. Ph.D. Dissertation, University of Georgia, Athens, GA.

Jackson, W. A., L. E. Asmussen, E. W. Hauser, and A. W. White. 1973. Nitrate in surface and subsurface flow from a small agricultural watershed. *J. Environ. Qual.* 2: 480–482.

Karr, J. R., and I. J. Schlosser. 1978. Water resources and the land–water interface. *Science* 201: 229–234.

Kuenzler, E. J., P. J. Mulholland, L. A. Ruley, and R. P. Sniffen. 1977. Water quality in North Carolina Coastal Plain streams and effects of channelization. *Water Resources Research Institute Report* No. 127. University of North Carolina, Raleigh, NC.

Lowrance, R. R., R. L. Todd, and L. E. Asmussen. 1983. Waterborne nutrient budgets for the riparian zone of an agricultural watershed. *Agric. Ecosyst. Environ.* 10: 371–384.

Omernik, J. M., A. R. Abernathy, and L. M. Male. 1981. Stream nutrient levels and proximity of agricultural and forest land to streams: some relationships. *J. Soil Water Conserv.* 36: 227–231.

Permar, T. A., and R. F. Fisher. 1983. Nitrogen fixation and accretion by wax myrtle (*Myrica cerifera*) in slash pine (*Pinus elliottii*) plantations. *For. Ecol. Manage.* 5: 39–46.

Schlosser, I. J., and J. R. Karr. 1981. Water quality in agricultural watersheds: impact of riparian vegetation during base flow. *Water Resour. Bull.* 17: 233–240.

Thornthwaite, C. W., and J. R. Mather. 1957. Instructions and tables for computing potential evapotranspiration and the water balance. *Drexel Institute of Technology, Publications in Climatology* 10: 185–311.

USFS. 1952. Forest Statistics for Southwest Georgia–1951. *US Dep. Agric. For. Serv. Res. Bull.* SE-37.

USFS. 1971. Forest Statistics for Southwest Georgia–1971. *US Dep. Agric. For. Serv. Res. Bull.* SE-19.

Verry, E. S., and D. R. Timmons. 1982. Waterborne nutrient flow through an upland-peatland watershed in Minnesota. *Ecology* 63: 1456–1467.

White, F. C., J. E. Hairston, W. N. Musser, H. F. Perkins, A. Ersoz, and J. F. Reed. 1980. Nonpoint source pollution and economic tradeoffs associated with rural land use changes in Georgia. *Univ. GA Coll. Agric. Expt. Sta. Res. Bull.* 260.