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NUTRIENT BUDGETS FOR AGRICULTURAL WATERSHEDS IN THE SOUTHEASTERN COASTAL PLAIN[1]

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Abstract. Watershed-level agroecosystem studies are essential to relate land management to the external environmental effects produced by agricultural nutrients and to enhance our understanding of agricultural nutrient cycles. Inputs and outputs of N, P, K, Ca, Mg, and Cl were determined for four subwatersheds of the Little River in the Georgia Coastal Plain from 1979 through 1981. The four watersheds had 40, 36, 54, and 50%, respectively, of their land in agricultural uses (row crop and pasture). Precipitation inputs and streamflow outputs were determined by field sampling of water volumes and nutrient concentrations. Agronomic inputs (from fertilizer and symbiotic N-fixation) and outputs in harvested material were estimated from land use data; countywide averages of fertilizer applications and crop yield; and plot studies on peanuts and soybeans. All elements except Cl had greater inputs than outputs on each watershed each year. The general order of streamflow loads was Cl > Ca > K > Mg > N > P. Fertilizer inputs exceeded precipitation inputs for all elements on all watersheds. Outputs of N, P, and K in harvest generally exceeded streamflow loads, but harvest outputs of Ca, Mg, and Cl were generally lower than streamflow loads. The two watersheds with more agricultural land had consistently higher loads of N, K, Ca, Mg, and Cl in streamflow and had NO_3-N loads 1.5 to 4.4 times higher than loads from the less agricultural watersheds. Streamflow loads on the Little River watersheds were similar to those on other Coastal Plain agricultural watersheds with comparable land use and discharge volumes. Budgets for the upland portion of one of the watersheds indicated that large amounts of N, P, K, Ca, and Mg were not accounted for. About 56 $kg \cdot ha^{-1} \cdot yr^{-1}$ of N were retained or lost to gaseous emissions from the uplands. Apparently, a large percentage of the nutrients applied to these watersheds was being retained somewhere in the watershed or being lost in some unquantified way.

Key words: *agroecosystems; calcium; chloride; Georgia Coastal Plain; magnesium; nitrate; nitrogen; nutrient cycling; phosphorus; potassium; watershed budgets; watersheds.*

Introduction

The study of nutrient budgets for watersheds has led to a better understanding of nutrient cycling within ecosystems. Bormann and Likens (1967) listed five advantages of studying properly selected watershed ecosystems:

1) Watersheds represent natural, easily definable ecosystems.

2) Properly selected and gaged watersheds permit evaluation of deep seepage and erosional nutrient losses.

3) The watershed approach makes the calculation of mineral budgets for an entire ecosystem possible.

4) This approach allows one to evaluate land-water interactions in the context of various land management policies.

5) Internal nutrient cycling processes and the role of individual ecosystems in larger biosphere processes can be examined.

When the watersheds under study are agricultural ecosystems occupied by a mosaic of agricultural and nonagricultural land uses, these advantages still exist but are complicated by the complexity and variability of intensive agricultural management systems. Difficulties of a watershed approach to agroecosystems include:

1) Watersheds can be defined by topographic boundaries, but many field-sized agroecosystems may exist within the topographic watershed.

2) Deep seepage may be minimal on certain watersheds but these watersheds may not adequately represent areas where deep seepage occurs. In addition, irrigation and artificial drainage can alter hydrologic conditions of agricultural watersheds.

3) Nutrient budgets are more difficult to calculate because of the inputs and outputs of nutrients, energy, and materials associated with agriculture. External factors (e.g., prices and other market variables) affect both inputs and outputs.

4) Individual crop fields exhibit seasonal, annual, and long-term nutrient dynamics in response to management. The complexity of an entire watershed may obscure management effects on land-water interactions.

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5) Distinct import and export pulses affect both the nature and rate of internal nutrient cycling processes on agricultural watersheds.

Despite these drawbacks, watershed-level agroecosystem studies are essential to relate land management to the external environmental effects produced by agricultural nutrients and to enhance our understanding of agricultural nutrient cycles. These studies can lead to more efficient nutrient use by farmers who face rising fertilizer costs, and to ecosystem management practices that maximize nutrient use in the entire topographic watershed.

Nutrients enter agricultural watersheds from a number of sources: precipitation, fertilizers, fixation from the atmosphere, irrigation, and weathering of soil parent material. Conversely, nutrients leave the watershed through streamflow, subsurface flow, deep seepage, the loss of volatile gases, and the harvest of plant and animal products. Nutrient budgets provide an assessment of the net watershed response to agricultural nutrient additions and removals. In this study we developed and compared watershed-level budgets of N, P, Cl, Ca, Mg, and K on four mixed-cover watersheds in the Georgia Coastal Plain. The budgets were developed by estimating inputs and outputs for each field-sized agroecosystem on the watershed based on average annual agronomic nutrient fluxes. Watersheds with different degrees of agricultural development were selected to determine the basin-level effects of agriculture on land-water interactions. The effect of annual differences in precipitation was demonstrated by annual differences in nutrient budgets. Budgets for 1979–1981 were developed for Watersheds N and O, and for 1980–1981 for Watersheds J and K. In addition, budgets were determined for the agricultural upland portion of Watershed N. The implications of these watershed budgets for water quality and nutrient cycling are discussed. Our purpose in discussing the effects of land use, management, and annual variability is not so much to understand control of the budget but to understand control of the watershed ecosystem response.

Study Area

The Little River Watershed (LRW) is located on the Tifton Upland of the Atlantic-Gulf Coastal Plain in Georgia (Fig. 1). Watersheds J, K, N, and O were used in this study. Most of the better drained upland soils (Plinthic Paleudults) support either intensive row crops, pastures, pine plantations (*Pinus elliottii*), or native pine forests (*P. palustris*). Crops include corn, soybeans, peanuts, sorghum, tobacco, and vegetables. The poorly drained bottomland soils (Plinthic Paleaquults) support either mixed hardwood forest, naturally seeded pines (*P. elliottii*), or, in some cases, pastures. The bottomland hardwood forest is dominated by *Nyssa sylvatica, Liriodendron tulipifera, Acer rubrum, Magnolia virginiana,* and *Quercus nigra* in the canopy, with *Myrica cerifera, Ilex glabra, Ligustrum sinense, Clethra alnifolia, Cliftonia monophylla, Lyonia lucida,* and other shrubs in the understory (Fail 1983). The soils are underlain by plinthic zones of lower permeability at 0.9–1.5 m; thus, much of the water movement is in a shallow unconfined phreatic aquifer. The water in this shallow aquifer moves into alluvial material in the bottomlands and is available for either recharge to the stream channel system, evapotranspiration, or movement off the watershed as subsurface flow. Previous studies (Lowrance et al. 1984*a*) showed that movement off the watershed in this shallow alluvial aquifer is $<1\%$ of streamflow. Other studies (Carlan et al. 1985) have indicated that nutrient movement off the watershed in deep seepage is negligible.

Materials and Methods

Streamflow was measured at a broad-crested v-notch weir on each watershed. Discharge was computed with rating equations that related stage (recorded at 5-min intervals) to flow volumes. Precipitation was measured with a network of 55 digital weighing and recording rain gages (Batten 1980). Nutrient loads in streamflow and precipitation were estimated by integrating water volumes with nutrient concentrations. Streamflow water quality samples were collected by a PS-69 automatic pumping sampler every 12 h from 1 January 1979 to 31 December 1981 from the stilling pond behind the weir on each watershed. Precipitation water quality samples were taken after each rainfall event at three locations on LRW. Concentrations of $NO_3 + NO_2$-N, NH_4-N, Cl, and dissolved molybdate-reactive phosphorus (DMRP) were analyzed by standard spectrophotometric techniques (APHA 1976). Total Kjeldahl N and total P were determined on a digestate (Technicon 1977); Ca, Mg, and K content were determined by atomic absorption spectrophotometry (Perkin Elmer 1980).

Land cover data were collected on Watersheds N and O by ground survey in summer beginning in 1979. Ground surveys of Watersheds J and K began in 1980. Area of each crop or other type of land use was determined by planimetry. Average fertilizer application rates and crop yields were estimated by the Tift and Turner County extension agents and were verified through interviews with farmers and fertilizer suppliers. Nutrient concentration of the harvested material was estimated from published sources (Brown and Ware 1958, NAS 1971, Tso 1972). Rates of symbiotic N-fixation in peanuts and soybeans were estimated from data of Hoyt (1981) for plots of these crops grown at the Coastal Plain Experiment Station near Tifton, Georgia.

Agronomic inputs and outputs for an average hectare of each crop were estimated from the data on fertilizer use, symbiotic N-fixation, yields, and nutrient concentrations in harvested material. Total agronomic inputs and outputs for a watershed were estimated by applying the average rates for each crop to the area of that crop

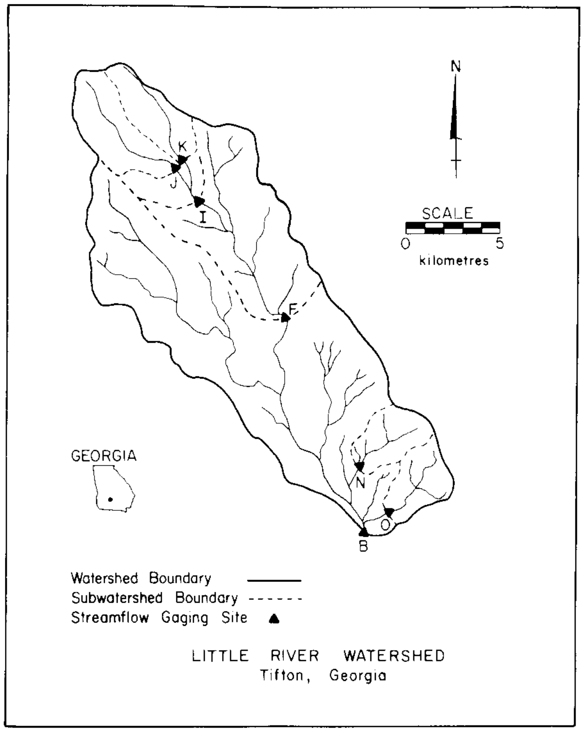

Fig. 1. Map of the Little River watershed showing locations of the weirs that define the lower limits of watersheds J, K, N, and O.

on the watershed and then summing these to obtain the total agronomic inputs and outputs for the watershed. These totals were then divided by total watershed area to obtain inputs and outputs per hectare. The nutrient budgets for the uplands of Watershed N were calculated by dividing the summed agronomic fluxes for each nutrient by the area of the uplands (1096 ha). Waterborne outputs from the upland in subsurface flow were estimated in a related study using a series of 37 shallow groundwater wells on nine transects on Watershed N (Lowrance et al. 1983). Each transect led from an upland field through the riparian zone to the stream channel. Wells were sampled after rainfall events or at least every two weeks between events in 1979, and nutrient concentrations were determined as described above for streamflow and precipitation.

In summary, nutrient budgets for entire watersheds were estimated by:

$$(\text{Precipitation} + \text{Fertilizer} + \text{Symbiotic N-fixation}) - (\text{Harvest} + \text{Streamflow}) = \text{Balance}.$$

For the upland area, streamflow was replaced by subsurface nutrient outputs.

Results and Discussion

Hydrology and land use

Eleven-year (1971–1981) averages of hydrologic records showed that less total runoff occurred from Watersheds N and O than from J and K (Table 1), but an analysis of variance ($\alpha = .05$) showed that the percentage of precipitation appearing as discharge did not differ significantly among the four watersheds. From these data, we conclude that the watersheds have similar hydrologic responses.

Land use on these four watersheds varied considerably (Table 1). Forested areas, including both bottomland hardwoods and upland pine forests, occupied 55 and 59% of Watersheds J and K, respectively. Forested areas on Watersheds N and O were almost totally bottomland hardwoods. Pasture and row crops occupied $\approx$50% of both Watersheds N and O. Apparently, differences in land use did not affect the hydrologic responses of these watersheds.

Nutrient budgets

Annual nutrient budgets for the four watersheds were calculated (Table 2). The balance column shows nutrients that were either retained on the watershed or lost through some unquantified pathway such as gaseous loss of N. Chloride, which is a "conservative" ion (Burton et al. 1977) and is not stored in large quantities by plants or soil, showed the lowest retention percentage on each watershed, except during 1981, when streamflow was lowest. Calcium and magnesium were applied in large quantiites in dolomite and complete fertilizers and had >80% of their input retained each year, except on Watershed O. Unaccounted or retained N ranged from 45 to 55% of input. Watershed O had relatively high streamflow loads of Ca, K, Mg, and Cl, probably due to the unquantified input of water and nutrients from a deep groundwater well. Load differences for Ca, Mg, K, and Cl between Watersheds N and O averaged 16.9, 3.7, 2.8, and 3.6 $kg \cdot ha^{-1} \cdot yr^{-1}$ respectively, for 1979–1981. We estimated that the groundwater well contributed $\approx$22.5, 2.8, 2.2 and 2.5 $kg \cdot ha^{-1} \cdot yr^{-1}$ of Ca, Mg, K, and Cl, respectively. Therefore, nutrient contributions from the well were approximately equal to the streamflow load differences.

Fertilizer inputs exceeded precipitation inputs for all

Table 1. Area, land use (percent of watershed), and 11-yr average (1971–1981) of precipitation and runoff for Watersheds J, K, N, and O.

	Watershed			
	J	K	N	O
Total area (ha)	2212	1666	1568	1593
Row crop (%)	36	34	41	32
Pasture (%)	4	2	13	18
Forest (%)	55	59	30	32
Other lands (%)*	5	5	16	18
Precipitation (mm)	1277	1266	1251	1238
Runoff (mm)	402	397	364	352
Runoff/precipitation (%)	31.5	31.4	29.1	28.4

* Includes roads, buildings, ponds, power lines, and experimental plots.

TABLE 2. Annual nutrient budgets for Watersheds N, O, J, and K. Balance = (Precipitation + Fertilizer) − (Streamflow + Harvest).

	Nitrogen ($kg \cdot ha^{-1} \cdot yr^{-1}$)					Phosphorus ($kg \cdot ha^{-1} \cdot yr^{-1}$)					Potassium ($kg \cdot ha^{-1} \cdot yr^{-1}$)				
	Inputs		Outputs			Inputs		Outputs			Inputs		Outputs		
	Precipitation	Fertilizer*	Streamflow	Harvest	Balance	Precipitation†	Fertilizer	Streamflow	Harvest	Balance	Precipitation	Fertilizer	Streamflow	Harvest	Balance
1979															
Watershed N	12.2	74.4	3.0	35.1	48.5	0.4	12.9	1.1	4.6	7.6	3.9	31.9	6.6	9.9	19.3
Watershed O	11.5	58.0	3.6	31.2	34.7	0.3	8.8	1.7	3.7	3.7	3.6	23.6	9.4	6.1	11.7
1980															
Watershed N	12.0	58.9	4.3	21.2	45.4	0.4	12.4	1.0	2.6	9.2	4.6	31.5	8.1	7.5	20.5
Watershed O	13.6	39.6	5.1	13.4	34.7	0.4	8.1	2.3	1.7	4.5	5.2	20.1	11.6	2.8	10.9
Watershed J	13.1	43.6	3.9	17.7	35.1	0.4	9.4	2.3	2.2	5.3	5.0	24.1	5.7	4.8	18.6
Watershed K	13.3	40.9	3.6	16.4	34.2	0.4	8.1	2.2	2.0	4.3	5.0	21.1	3.1	3.5	19.5
1981															
Watershed N	11.0	80.2	0.4	32.4	58.4	0.3	15.6	0.7	3.9	11.3	3.8	38.5	2.1	11.5	28.7
Watershed O	10.6	50.0	0.5	19.7	40.4	0.3	8.5	0.2	2.5	6.1	3.8	20.6	4.1	4.7	15.6
Watershed J	11.2	58.1	0.1	21.0	48.2	0.3	9.5	0.1	2.9	6.8	4.0	21.4	0.6	4.2	20.6
Watershed K	10.6	48.3	0.1	27.8	31.0	0.3	6.8	0.1	2.9	4.1	3.7	20.6	0.8	5.6	17.9

	Calcium ($kg \cdot ha^{-1} \cdot yr^{-1}$)					Magnesium ($kg \cdot ha^{-1} \cdot yr^{-1}$)					Chloride ($kg \cdot ha^{-1} \cdot yr^{-1}$)				
	Inputs		Outputs			Inputs		Outputs			Inputs		Outputs		
	Precipitation	Fertilizer	Streamflow	Harvest	Balance	Precipitation	Fertilizer	Streamflow	Harvest	Balance	Precipitation	Fertilizer	Streamflow	Harvest	Balance
1979															
Watershed N	5.2	94.6	9.0	2.4	88.4	1.4	48.2	4.2	2.2	43.2	10.5	23.9	27.3	0.8	6.3
Watershed O	4.9	72.8	27.9	1.2	48.6	1.3	34.6	8.1	1.7	26.1	10.3	17.7	30.8	0.3	−3.1
1980															
Watershed N	9.5	90.2	10.7	2.3	86.7	1.9	43.6	5.0	1.3	37.3	8.5	23.6	28.7	1.7	1.7
Watershed O	11.0	65.0	27.1	0.5	48.4	2.2	31.3	9.0	0.8	23.7	9.7	15.1	35.3	0.2	−9.7
Watershed J	11.9	81.2	7.6	1.2	84.3	2.3	37.2	3.7	1.1	34.7	10.2	18.1	27.0	0.6	0.7
Watershed K	12.0	74.8	6.5	0.8	79.5	2.4	34.1	4.1	1.0	31.4	10.5	15.8	26.9	0.3	−0.9
1981															
Watershed N	7.4	98.3	2.2	3.3	100.2	1.9	48.7	1.9	2.0	46.7	11.4	28.9	10.4	1.8	28.1
Watershed O	7.1	65.8	17.6	0.8	54.5	1.9	30.8	5.1	1.2	26.4	11.0	15.4	11.2	1.2	14.0
Watershed J	8.2	78.7	0.7	0.7	85.5	1.9	36.4	0.9	1.3	36.1	12.7	16.0	5.8	0.2	22.7
Watershed K	7.7	71.1	0.7	1.6	76.5	1.7	32.3	0.9	1.5	31.6	11.9	15.4	5.8	0.6	20.9

* Includes symbiotic N-fixation.
† Dissolved molybdate-reactive phosphorus only.

nutrients on all watersheds. Fertilizer inputs differed from precipitation inputs in that they varied more over the watershed and were concentrated in both space and time. Therefore, watersheds responding primarily to fertilizer inputs would be expected to differ from watersheds depending more on precipitation nutrient inputs. More of the major plant nutrients, N, P, and K, left the watershed through harvest than through streamflow. Conversely, Ca, Mg, and Cl levels are relatively low in the harvested plant parts and there were higher exports of these elements in streamflow (Table 2).

Analysis of the budgets may indicate the sources of the largest absolute errors. Both absolute and relative error in fertilizer and harvest measurements were greater than in precipitation and streamflow. Larger amounts of N than of the other elements were removed in harvest due to higher concentrations of N in harvested material. Therefore, if large absolute errors in the N budget exist, they may be due to fertilizer and/or harvest measurements. If large absolute errors in the P, K, Ca, Mg, and Cl budgets exist, the source is likely to be fertilizer values, since concentrations of these elements in harvested plant parts were very low and overall harvest outputs were small.

Analysis of inputs, outputs, and balances for all nutrients showed significant positive correlations (0.05 level) between fertilizer and harvest levels of N, Cl, Ca, Mg, and K, and also between fertilizer and balance levels of N, P, Ca, Mg, and K. These results imply that harvest levels were positively related to fertilizer inputs when both were estimated on a watershed basis and that the balances (unaccounted nutrients) were related to the quantity of nutrients applied. Only Cl, which is biologically inactive and not retained at high levels in soil (Tullock et al. 1975), did not exhibit an increase in surplus with an increase in fertilizer applications. Increased streamflow loads decreased the surplus of Ca, Mg, and K, but had no significant effect on N, Cl, and P. A positive relationshp between balance and harvest levels for Ca, Mg, and K was found, since fertilizer contributed to both harvested and surplus

TABLE 3. Nutrient balance (input − output) on watersheds in other studies and Watersheds N and K in this study. All nutrient units $kg \cdot ha^{-1} \cdot yr^{-1}$. Dash indicates not measured.

Nutrient species	Henderson et al. 1977*	Burton et al. 1977*	Swank and Douglas 1977*	Correll et al. 1977*	Watershed N†	Watershed K†
Cover (% forest/% agriculture)	100/0	50/50	100/0	47/38	30/54	59/36
Cl	—	5.80	−0.73	—	15.0	10.0
NO_3-N	3.70	2.10	2.87	—	2.4‡	3.1‡
NH_4-N	1.70	1.54	1.97	—	2.9‡	3.2‡
Organic N	5.20	—	—	—	3.6‡	4.2‡
Total N	6.90	—	—	17.5	57.7	32.3
DMRP§	—	−0.06	0.07	—	0.2‡	0.3‡
Total P	0.52	0.03	—	4.9	13.5	7.9
Ca	−133.20	—	−2.96	47.8	93.4	78.0
Mg	−75.00	—	−2.71	6.9	43.8	31.6
K	−3.70	—	−3.45	−4.4	24.6	18.8

* Includes only precipitation inputs and streamflow outputs.
† Includes fertilizer and precipitation inputs and streamflow and harvest outputs for 1980 and 1981 unless otherwise noted.
‡ Includes only precipitation and streamflow for 1979–1981.
§ Dissolved molybdate-reactive phosphorus.

nutrients. Precipitation input had a significant positive effect on streamflow loads of N and P, but had no effect on Ca, Mg, and K and a negative effect on Cl in streamflow. Fertilizer and streamflow loads were not significantly positively related for any element, which indicates that other processes controlled nutrient output in streamflow.

Even though these correlations are not totally explicable in terms of what we know about nutrient behavior, the high correlations between fertilizer and harvest values strengthen the case for using these estimates. Fertilizer and harvest data were countywide averages based on standard fertilizer formulations for each crop and average nutrient concentrations of plant parts. Unless both fertilizer and harvest data were biased in the same direction, they should not correlate so well. The correlations between nutrient levels in fertilizer and harvest and between those in fertilizer and balance were probably due to the amount of land in agriculture, since there was little variability in fertilizer management practices from watershed to watershed. The field, farm, or landscape response (i.e., nutrient export) was dominated by the removal of harvested material. The watershed response (i.e., nutrient export over the weir) was not clearly dominated by fertilizer inputs but was due to interactions among the ecosystem components of the watershed.

The nutrient balances (input-output) of other watersheds were compared to those of Watersheds N and K (Table 3). Ca, Mg, and K were lost from both watersheds whose only nutrient inputs came from precipitation. The Rhode River Watershed (Correll et al. 1977) retained Ca and Mg (positive balance) but lost K (negative balance) when fertilizer inputs were included in the budget. Both Rhode River and Little River are in Coastal Plain agricultural areas with soils of low cation exchange capacity. All watersheds (Table 3) retained at least one form of N, with higher retention rates on the watersheds that received fertilizer N. Watersheds N and O had consistently higher retention rates than all other watersheds, due primarily to high loadings from agronomic sources.

The influence of the quantity and timing of precipitation on both the production of streamflow runoff and the yield of agricultural crops is reflected in these budgets (Table 2). Rainfall during 1979 (1238 mm) was close to the 50-yr average of 1203 mm (Batten 1980) and was well distributed throughout the year (Fig. 2). In 1980 heavy rains and large runoff events took place during the spring, but drought conditions during summer diminished crop yields and nutrient output in harvest. In 1981 the drought continued through the spring and reduced runoff, but yields were close to normal due to adequate summer rain (Fig. 2 and Table 2). Fertilizer applications for 1981 may have been overestimated since some farmers decreased applications for that growing season due to reduction of yields in 1980. Farmers probably reduced fertilizer applications only slightly in 1981 for a number of reasons: (1) some farmers, especially those with irrigation, had nearly normal yields in 1980, (2) even low winter rainfall (1980–1981) would still leach the more soluble nutrients out, and (3) after a poor year in 1980, farmers would not be willing to risk too little fertilizer in 1981.

Even though each watershed had large inputs and outputs of agronomic nutrients, there were higher loads of N in precipitation than streamflow each year. Thus, even on the most heavily agricultural watersheds, buffering by nutrient cycling processes decreased outputs to below the "natural" inputs. Loads of P, Ca, Mg, K, and Cl were higher in streamflow than in precipitation in 1979 and 1980 (Table 2). When runoff was reduced in 1981, all elements except Mg had higher loads in precipitation. The order of streamflow loads was Cl > Ca > K > Mg > N > P each year. Apparently the vegetation and soils of the watershed have a large "buffer capacity" for N and P, less capacity to buffer inputs of Mg, K, and Ca, and little effect on Cl inputs.

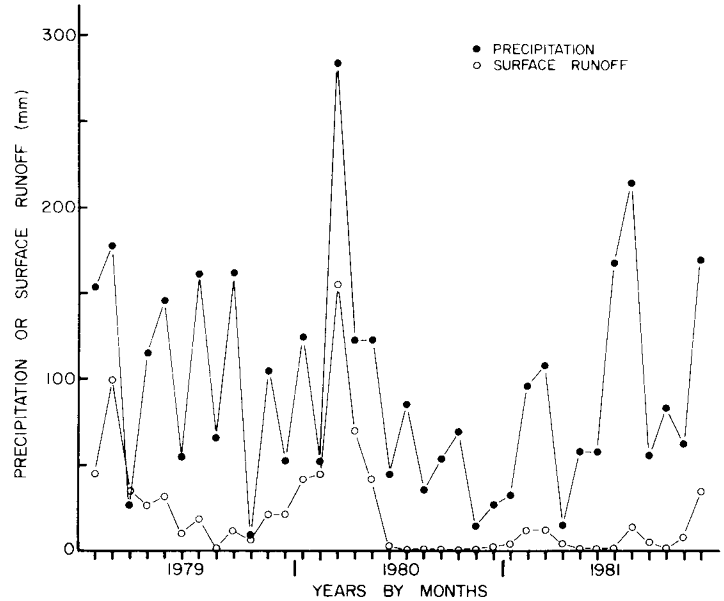

FIG. 2. Monthly totals of precipitation and streamflow runoff for Watershed N during 1979–1981.

Correll et al. (1977) found higher loads of P, K, Ca, and Mg in runoff than in precipitation on the Rhode River Watershed in Maryland. Ca, Mg, and K in streamflow exceeded precipitation levels on unfertilized forested watersheds in North Carolina (Swank and Douglass 1977), although Cl was approximately balanced.

Streamflow loads

Loads of N, K, Ca, Mg, and Cl in streamflow were higher on Watersheds N and O than on J and K (Table 2) even though total flows for 1980–1981 were approximately equal (Table 4). Leonard et al. (1982) found that concentrations of N, P, and K were higher on Watershed N than on Watersheds J and K. These higher loads and concentrations may have been due to the greater percentage of land in row crops and pasture on Watersheds O and N, and greater areas of forest on Watersheds J and K. Mean monthly concentrations of N, Ca, Mg, and K were significantly higher in the phreatic aquifer under row crop fields than under forest for each month during 1979 on Watershed N (Lowrance et al. 1984*a*). These higher concentrations in subsurface flow, coupled with the higher probability of surface runoff from row crop areas than from forest, would be expected to lead to higher nutrient loads from the two more heavily agricultural watersheds.

In 1979 and 1980, streamflow loads of organic N

TABLE 4. Annual flow and loads of N and P species for Watersheds J, K, N, and O in 1979–1981.

	Flow (mm)	Streamflow loads ($kg \cdot ha^{-1} \cdot yr^{-1}$)						NO_3-N / Organic N (%)	DRMP* / Total P (%)
		NO_3-N	NH_4-N	Organic N	Total N	DMRP*	Total P		
1979									
J	464	0.222	0.127	2.697	3.047	0.083	1.494	8.2	5.6
K	437	0.255	0.084	2.514	2.853	0.079	1.195	10.1	6.6
N	334	0.694	0.055	2.822	3.571	0.090	1.030	24.6	8.7
O	306	0.959	0.162	2.753	3.874	0.090	0.874	34.8	10.3
1980									
J	430	0.672	0.122	3.148	3.942	0.219	1.191	21.3	18.4
K	427	0.390	0.079	3.102	3.571	0.140	1.086	12.6	12.8
N	363	1.060	0.075	3.180	4.315	0.187	1.009	33.3	18.5
O	382	1.303	0.219	3.619	5.141	0.244	1.016	36.0	24.0
1981									
J	50	0.004	0.007	0.051	0.061	0.015	0.033	7.8	45.4
K	39	0.019	0.010	0.039	0.068	0.004	0.029	48.7	13.8
N	107	0.207	0.025	0.154	0.386	0.015	0.097	134.4	15.5
O	117	0.205	0.099	0.191	0.494	0.029	0.115	107.3	25.2

* Dissolved molybdate-reactive phosphorus.

TABLE 5. Dissolved nutrient loads from other forested and agricultural watersheds and Watersheds N and K in this study. All nutrient loads are $kg \cdot ha^{-1} \cdot yr^{-1}$. Dash indicates not measured.

	Burton et al. 1977	Swank and Douglas 1977	Correll et al. 1977 (1975–1976 data)	Overcash et al. 1977 (W-10)	Overcash et al. 1977 (P-8)	Campbell 1982 (Lower 1976–1979 data)	Campbell 1982 (Upper 1976–1979 data)	Watershed N (this study, 1979–1980 data)	Watershed K (this study, 1979–1980 data)
Size (ha)	611	12	983	1650	1170	437	645	1568	1666
Flow (mm)	168	1250	354	370	300	65	59	349	432
Row crop and pasture (%)	50	0	38	50	22	37	53	54	36
Forest (%)	50	100	47	49	77	63	47	30	59
Cl	8.10	7.50	–	–	–	–	–	28.03	30.86
NO_3-N	0.08	0.05	–	–	–	0.13	0.09	0.88	0.32
NH_4-N	0.07	0.05	–	–	–	0.10	0.08	0.07	0.08
Organic N	–	–	–	–	–	1.52	1.52	3.00	2.81
Total N	–	–	3.81	4.40	4.20	1.75	1.69	3.95	3.21
DMRP*	0.15	0.02	–	0.36	0.31	0.41	0.37	0.14	0.11
Total P	0.38	–	0.91	–	–	0.53	0.84	1.02	1.14
Ca	–	7.74	2.12	–	–	–	–	9.82	6.75
Mg	–	3.71	9.86	–	–	–	–	4.61	4.58
K	–	5.59	17.10	–	–	–	–	7.38	3.41

* Dissolved molybdate-reactive phosphorus.

were approximately the same on all watersheds, but loads of NO_3-N were 1.5 to 4.4 times higher on Watersheds O and N than on Watersheds J and K (Table 4). In 1981, the year of very low flow, NO_3-N was 10–50 times higher on Watersheds O and N than on J and K. As a percentage of organic N load, the level of NO_3-N also increased, and it actually exceeded the organic N level on Watersheds O and N. Apparently, low rainfall and conditions of no flow from July through December 1980 and from May through July 1981 (Fig. 2) affected N loads both through reduced flow volumes and through changes in the proportion of N load carried in organic and inorganic forms. Total flow decreased by 70%, and levels of NH_4-N, NO_3-N, and organic N by 58, 82, and 95%, respectively, on Watersheds O and N from 1980 to 1981. Therefore, NH_4-N decreased less than flow, NO_3-N decreased slightly more than flow, and organic N decreased much more than flow or the inorganic N forms. These differences may be related to differences in the timing of streamflow during the two years (Fig. 2). There was almost no flow after May in 1980 but there was high streamflow in the winter and spring. In contrast, a greater proportion of the total annual streamflow in 1981 occurred in August, November, and December. The proportionally higher load of organic N during 1980 may have been due to more leaching of N-containing organic compounds from bottomland forest litter during late 1979 and early 1980 and subsequent movement of these compounds in streamflow. Since most 1981 streamflow took place after an extended drought, there was less opportunity for leaching of organic compounds.

Total N loads on Watersheds N and O were higher than on Watersheds J and K for all three years, but in each year the largest difference was found in NO_3-N and NH_4-N (Table 4). Other studies on Watershed N (Lowrance et al. 1983) indicate that row crops were the primary source of NO_3-N while pastures contributed more NH_4-N. The relatively large proportion of Watershed O devoted to pasture apparently increased loads of NH_4-N, while high percentages of cropland on Watershed N increased NO_3-N loads. Even though inorganic N remained less than half of organic N loads on all watersheds in the two higher flow years, it is obvious that larger areas of cropland and pasture increased the relative load of inorganic N.

Total P loads on Watersheds N and O were generally slightly lower than on Watersheds J and K, except during 1981 (Table 4). Loads of DMRP as a percentage of total P were $\leq$25% except on Watershed J during 1981. Loads of DMRP on Watershed O were highest each year and generally were a higher percentage of total P. Apparently, total P was not affected by the increased crop and pasture area on Watersheds N and O, at least during the highest flow years. Therefore, transport of a less soluble nutrient (P) was not affected by land use, while levels of the more soluble inorganic N were higher on Watersheds N and O.

Loads of nutrients on Watersheds N and K are compared to loads found in other studies in Table 5. Loads of N, P, and Ca were higher on the Little River watersheds than on the Rhode River watershed (Correll et al. 1977). Loads of Mg and K were much higher on the Rhode River watershed, although Watershed N had a larger proportion of land in crops and pasture. Burton et al. (1977) reported NO_3-N loads only 1/10 of those on Watershed N, a difference much greater than the difference in flow volumes. Compared to data of Swank and Douglas (1977) for Coweeta, North Carolina, the agricultural lands on Watersheds N and K had the greatest effect on loads of Cl and NO_3-N. Watershed N had a 17 times greater load of NO_3-N although the forested watershed at Coweeta had three times the flow

FIG. 3. Composite air photo of Watershed N showing the upland agricultural areas (lighter) and the riparian forest ecosystem (darker).

of Watershed N. In general, when compared to other watersheds with similar runoff volumes and similar cropland proportions, the Little River watershed had loads similar to those reported in other studies. Watersheds with much lower flows (Burton et al. 1977, Campbell 1982) generally have much lower loads.

Upland nutrient budgets

Watershed N can be divided into a 472-ha riparian forest zone and a 1096-ha upland agricultural area. These areas of different land use form a distinct pattern when seen from the air (Fig. 3). Nutrient budgets for 1979 for the upland area, including data on subsurface nutrients from Lowrance et al. (1983) are shown in Table 6. Retained or unaccounted nutrients in each hectare of uplands (Table 6) were greater than for an average hectare from the entire watershed (Table 2). Only 17% of the Cl input was retained; thus, an element that is biologically inactive and is not fixed in the soil in large amounts had less retention. The retained or unaccounted nutrients may have been stored in or lost from the uplands in a number of ways: surface movment in runoff and erosion; leaching with subsequent storage in lower soil horizons; and loss of nitrogen through microbial and chemical denitrification and other gaseous emissions. Previous studies showed that between 80 and 96% of the total runoff from upland areas occurs as subsurface flow and that 99% of the NO_3-N movement from fields is in subsurface flow (Jackson et al. 1973, Lowrance et al. 1984*a*). Surface runoff from cropland may have been more important in the transport of P and K into the riparian zone, although sediment P accounted for <10% of the total streamflow P load in 1979 (Lowrance et al. 1984*b*).

TABLE 6. Nutrient budgets for Watershed N upland in 1979. Balance = (Precipitation + Fertilizer) − (Subsurface + Harvest).

	Nutrient flows ($kg \cdot ha^{-1} \cdot yr^{-1}$)					
	N	P	K	Ca	Mg	Cl
Precipitation	12.2	3.5	3.9	5.2	1.4	10.5
Fertilizer*	106.5	18.5	46.7	135.4	69.0	34.2
Subsurface flow†	12.5	0.9	8.4	20.4	7.1	35.9
Harvest	50.2	6.6	14.2	3.4	3.1	1.1
Balance	56.0	14.5	28.0	116.8	60.2	7.7

* Includes symbiotic N-fixation.
† Lowrance et al. (1983).

Ca and Mg were apparently accumulated at a depth of between 30 and 90 cm in the soil profile. Increases over surface soil levels (Carter 1981) of up to 18 mg/100 g soil for Mg, and up to 30 mg/100 g soil for Ca were found in the subsurface horizons. These accumulations are associated with increases in percent clay and cation exchange capacity at depth. Subsoil with an average bulk density of 1.5 g/cm^3 would contain ≈2700 kg/ha of Ca and 1640 kg/ha of Mg in the 30–60 cm horizon due to an accumulation of cations. The magnitude of this accumulation indicates that some of the Ca and Mg was retained in these subsoils. Sites with a history of liming had higher levels of Ca and Mg than forest sites, indicating that agricultural management has led to the long-term accumulation of these cations (Carter 1981). Carlan et al. (1985) found that K is fixed on exchange sites above the plinthic horizon on soils of the watershed.

Field studies of denitrification in agroecosystems have produced estimates ranging from 0 to 100% of leached nitrates denitrified (Meek et al. 1969, Pratt and Adriano 1973). Gambrell et al. (1975) showed that most of the N not taken up by crops in agricultural systems in the North Carolina Coastal Plain was not available in the next growing season, and speculated that up to 60 $kg \cdot ha^{-1} \cdot yr^{-1}$ of N could be denitrified on poorly drained Coastal Plain soils. Ten-year nitrogen budgets for a 0.34-ha research plot (Watershed Z) in Tifton show that between 50 and 74 $kg \cdot ha^{-1} \cdot yr^{-1}$ are not accounted for (Hubbard and Sheridan 1983; R. R. Lowrance, *personal observation*). It is not clear how much of this "missing" nitrogen was lost to denitrification, but the unaccounted nitrogen per unit area on Watershed Z was greater than the annual retention on Watershed N.

Conclusions

It is apparent from nutrient budgets that Watersheds J, K, N, and O were either accumulating nutrients or, in the case of nitrogen, losing nutrients via dentrification or ammonia volatilization, pathways that were not adequately quantified. Decreased precipitation reduced the outputs in two ways: by decreasing streamflow and lowering harvest yields. Loads of N, P, K, Ca, and Mg in streamflow on the most heavily cropped watershed (N) were higher than for more heavily forested watersheds (J and K). Greater areas in cropland and pastureland on Watersheds N and O increased loads of inorganic N but did not affect loads of P. The highest loads in streamflow came from Watershed O, which had flow augmented by a deep groundwater well. All watersheds except Watershed K had elements transported in streamflow in the same relative quantities; Cl > Ca > K > Mg > N > P.

The complex input and output environments of agricultural watersheds make nutrient budgets difficult to estimate and make it impossible to use watershed budgets to estimate weathering and deep seepage. The preponderance of inputs in these agroecosystems came from anthropogenic sources, and outputs of N, P, and K were dominated by harvest removal. Other studies on LRW and the N budgets for these watersheds indicate that 50–75 $kg \cdot ha^{-1} \cdot yr^{-1}$ may be lost via dentrification and other gaseous emissions.

The large quantities of N, Ca, Mg, and K that enter these watersheds but are not removed in harvest represent an inefficient use of nutrient resources. The economic effect of this inefficiency is especially significant for nitrogen due to the high cost of synthetic nitrogen fertilizers. This study points out that watershed-level processes that help to maintain water quality might also cause field-scale fertilizer use efficiency to be low. Optimum management strategies would allow nutrient loads in streams to remain low or to be reduced while increasing the proportion of nutrient inputs used by crops. More intensive cropping of upland agricultural fields might lead to more efficient nutrient use by maintaining actively growing crops for more of the growing season. Conversely, less intensive use of croplands and expansion of forests might have similar effects on streamflow nutrient outputs. The more intensive strategy would probably yield greater economic return and thus is a more likely future scenario.

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Literature Cited

APHA. 1976. Standard methods for the examination of water and wastewater. 14th edition. American Public Health Association, Washington, D. C., USA.

Batten, H. L. 1980. Little River research watersheds. United States Department of Agriculture Miscellaneous Publication **48**.

Bormann, F. H., and G. E. Likens. 1967. Nutrient cycling. Science **155**:424–429.

Brown, H. B., and J. O. Ware. 1958. Cotton. McGraw-Hill, New York, New York, USA.

Burton, T. M., R. R. Turner, and R. C. Harriss. 1977. Nutrient export from three north Florida watersheds in contrasting land use. Pages 323–341 *in* D. L. Correll, editor. Watershed research in eastern North America. Smithsonian Institution, Edgewater, Maryland, USA.

Campbell, K. L. 1982. Nutrient transport from North Florida agricultural fields and watersheds. Pages 14–27 *in* Special symposium on agriculture and water quality in Florida. Institute of Food and Agricultural Sciences, Gainesville, Florida, USA.

Carlan, W. L., H. F. Perkins, and R. A. Leonard. 1985, *in press*. Tracing movement of water within plinthic soil material using bromide. Soil Science.

Carter, E. A. 1981. Effect of slope and landscape upon selected soil properties in the Coastal Plain. Thesis. University of Georgia. Athens, Georgia, USA.

Correll, D. L., T. L. Wu, E. S. Friebele, and J. Miklas. 1977. Nutrient discharge from Rhode River watersheds and their relationships to land use patterns. Pages 413–434 *in* D. L. Correll, editor. Watershed research in eastern North America. Smithsonian Instituion, Edgewater, Maryland, USA.

Fail, J. L. 1983. Structure, biomass, production, and element accumulation in riparian forests of an agricultural watershed. Dissertation. University of Georgia, Athens, Georgia, USA.

Gambrell, R. P., J. W. Gilliam, and S. B. Weed. 1975. Denitrification in subsoils of the North Carolina Coastal Plain as affected by soil drainage. Journal of Environmental Quality **4**:311–316.

Henderson, G. S., A. Hunley, and W. Selvidge. 1977. Nutrient discharge from Walker Branch Watershed. Pages 307–320 *in* D. L. Correll, editor. Watershed research in eastern North America. Smithsonian Institution, Edgewater, Maryland, USA.

Hoyt, G. D. 1981. Nitrogen cycling in a southeastern Coastal Plain agricultural ecosystem. Dissertation. University of Georgia, Athens, Georgia, USA.

Hubbard, R. K., and J. M. Sheridan. 1983. Water and nitrate-nitrogen losses from a small Coastal Plain watershed. Journal of Enviornmental Quality **12**:291–295.

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. Journal of Environmental Quality **2**:480–482.

Leonard, R. A., R. L. Todd, L. E. Asmussen, and V. A. Ferreira. 1982. Water quality and nutrient cycling in Coastal Plain watersheds. Pages 201–210 *in* E. G. Kruse, C. R. Burdick, and Y. A. Yousef, editors. Environmentally sound water and soil management. American Society of Civil Engineers, New York, New York, USA.

Lowrance, R. R., R. L. Todd, and L. E. Asmussen. 1983. Nutrient budgets for the riparian zone of an agricultural watershed. Agriculture, Ecosystems, and Environment **10**: 371–384.

Lowrance, R. R., R. L. Todd, and L. E. Asmussen. 1984*a*. Nutrient cycling in an agricultural watershed: I. Phreatic movement. Journal of Environmental Quality **13**:22–27.

Lowrance, R. R., R. L. Todd, and L. E. Asmussen. 1984*b*. Nutrient cycling in an agricultural watershed: II. Streamflow and artificial drainage. Journal of Enviornmental **13**: 27–32.

Meek, B., A. MacKenzie, and L. Grass. 1969. Applied nitrogen losses in relation to oxygen status of soils. Soil Science Society of America Proceedings **33**:575–578.

NAS. 1971. Atlas of nutritional data of United States and Canadian feeds. National Academy of Science, Washington, D. C., USA.

Overcash, M. R., L. Bliven, F. Koehler, J. W. Gilliam, and F. J. Humenik. 1977. Nutrient yield assessment by different sampling strategies. Pages 365–381 *in* D. L. Correll, editor. Watershed research in eastern North America. Smithsonian Institution, Edgewater, Maryland, USA.

Perkin-Elmer. 1980. Procedures for use of atomic absorption spectrophotometer. Perkin-Elmer Corporation, Norwalk, Connecticut, USA.

Pratt, P. F., and D. C. Adriano. 1973. Nitrate concentrations in the unsaturated zone beneath irrigated fields in southern California. Soil Science Society of America Proceedings **37**: 321–322.

Swank, W. T., and J. E. Douglass. 1977. Nutrient budgets for undisturbed and manipulated hardwood forest ecosystems in the mountains of North Carolina. Pages 343–362 *in* D. L. Correll, editor. Watershed research in eastern North America. Smithsonian Institution, Edgewater, Maryland, USA.

Technicon. 1977. Technicon industrial method number 376-75 W/B. Technicon Industrial Instruments, Tarrytown, New York, USA.

Tso, T. C. 1972. Physiology and biochemistry of tobacco plants. Dowden, Hutchinson and Ross, Stroudsburg, Pennsylvania, USA.

Tullock, R. J., N. T. Coleman, and P. F. Pratt. 1975. Rate of chloride and water movement in Southern California soils. Journal of Environmental Quality **4**:127–131.