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A regional analysis of total nitrogen in an agricultural landscape

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Abstract

Techniques for modeling spatial variability in the loss, gain, and storage of total nitrogen (N) in an agricultural landscape were developed utilizing a geographic information system (GIS) based on the Map Analysis Package (C.D. Tomlin, Yale University). The study area is a well-monitored portion (upper 114.9 km^2) of the Little River Watershed, located near Tifton, Georgia, U.S.A. On the basis of measured N in the soil and vegetation, and the gains and losses of N by stream discharge, fertilizer, precipitation, N fixation, crop harvest, etc., it was possible to quantify and map source and sink regions of Total N, and to calculate a mass balance of N for an entire year. Results indicate massive flows of N, especially from anthropogenic sources. However, for the watershed as a whole, the N is virtually in balance with a small accretion occurring mostly in the riparian zones. Stream discharge of total N indicates that this landscape is well-buffered against excessive losses of N despite the large agricultural inputs.

Introduction

Despite massive measurement and modeling efforts using both laboratory and field techniques, little is known about the spatial variability of nitrogen dynamics across entire landscapes, especially complex agricultural landscapes (Newbound 1981). Numerous studies have measured the chemical composition of water flowing out of watersheds, and often this discharge is related to land use or to some experimental treatment of a watershed (Omernik 1977; Borman and Likens 1970; Lowrance *et al.* 1983). The majority of previous nitrogen cycling studies have investigated dynamics of specific sites. Thus the best information on nitrogen dynamics is available at the kilometer scale of monitored watersheds and the meter scale of intensively measured sites or plots.

The problem of modeling the input, storage, and output of an element at the landscape level of resolution is difficult to solve because sampling and measurement techniques have not been designed to adequately capture the spatial variability across an entire landscape. One solution is to estimate the storages and transfers of an element on the basis of some easily determined landscape variable, such as land use, land cover, soil type, precipitation, etc. The use of a deductive approach is warranted due to recent advances in the study of nitrogen dynamics in a variety of landuse types (Meentemeyer and Kesner 1984). It should be noted, however, that this approach is limited by the reliability and completeness **of** representative field measurements and estimates. Nevertheless, watersheds which have been studied and monitored for a number of years, such as the Little River Watershed (LRW) in Southern

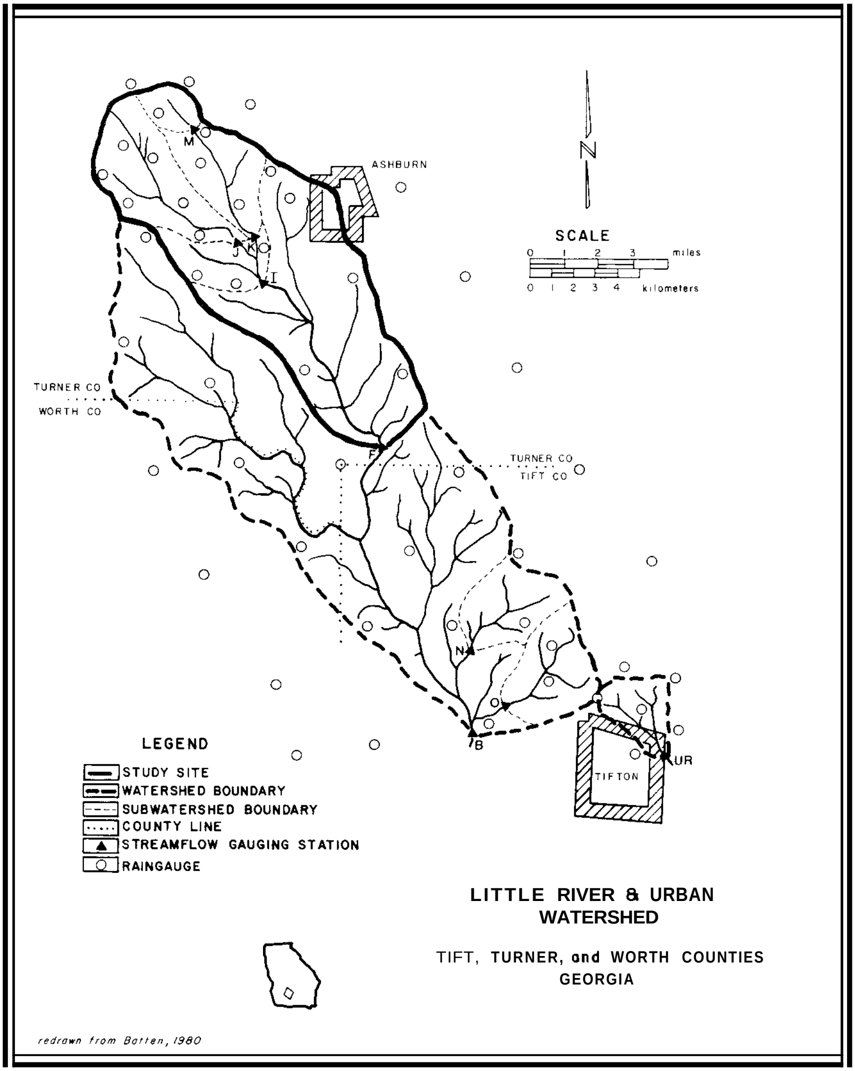


***Fig.** 1.* Map of the Little River Watershed (Tift, Turner and Worth Counties) near Tifton, Georgia. The study area (Watershed F) comprises the upper 114.0 km' of the watershed.

Georgia, USA, are especially appropriate for this first attempt.

It is the primary purpose of this paper to present cartographic models of the spatial patterns of nitrogen balance in an agricultural watershed. To execute this approach, a geographic information system (GIS), the Map Analysis Package (MAP) (Tomlin 1980)is used to organize and retrieve information on the myriad land use and environmental variables present on the Little River Watershed. Use of a GIS permits spatial analyses of total N input, output, net balance, storage, and time for 'total system turnover' for an entire landscape. In addition, the planimetric capabilities of MAP are used to compile estimates of the total nitrogen input, storage, and loss for the study area. By subtracting maps of total input from total loss, it is possible to determine whether the LRW is losing or gaining nitrogen. Totals based on the GIS and actual measurements will then be compared with estimates of net gains and losses which were calculated by other researchers using a variety of extrapolation methods. In addition, the estimated net totals are compared with the measured nitrogen loss via streamflow.

Study area

Little River Watershed (LRW), near Tifton, Georgia, U.S.A. is a 334 km^2 drainage basin in the Tifton Upland subprovince of the Atlantic Gulf Coastal Plain (Fig. 1). LRW is located at 31°30′N latitude, 83°35′W longitude. The drainage network of the Little River is generally dendritic, and flows in a southeasterly direction through an area of relatively low relief, dropping approximately 2 m per km. Little River flows through a poorly defined channel forming broad, flat, alluvial floodplains characteristic of the branch swamp regions of the Georgia coastal plain (Wharton 1978).

Soils in the upland regions of the watershed generally have high infiltration rates (15–50 cm/hr). They are underlain by zones of lower permeability, which serve as an aquilude at depths of 0.9–1.5 m. Therefore, much of the precipitation infiltrates and moves laterally as phreatic water above the impermeable zone (Lowrance 1981). Bottomland areas consist of deep, poorly drained soils formed in drainages and depressions adjacent to the Little River and its tributaries. The water table is usually within 1.0 m of the surface from late autumn to spring.

The portion of the LRW selected for this study is Watershed F, a 114.9 km^2 area comprising the headwater of the Little River. The make-up of Watershed F is approximately 42% row crops, 41% forested, 6% pasture, 5% idle, and 6% in homesites and lakes. The upland fields tend to be less than 16 ha (40 acres) in size, and are divided by the major dendritic tributaries of Little River. Major crops in the area are peanuts, corn, and soybeans, with small localized areas of tobacco, cotton, pecan orchards and vegetable crops. Much of the cropland, is sown in rye or winter wheat for winter cover and some cover crops are often grazed through early spring. Pastures are usually planted in either bahia or bermuda grass, and are grazed all year (Batten 1980).

Slash pine (*Pinus elliottii*) is the dominant species in planted pine communities. A swamp hardwood or riparian forest is found in the coastal plain landscape as a transition between dry upland areas and the stream channels. Fail (1983) described these regions as ‘streamside forests growing in low-lying areas subject to periodic flooding from free flowing streams’. These forests are situated adjacent to upland areas, and may be subjected to some grazing activities and wood harvest.

The major species of these riparian forest areas are: slash Pine (*P. elliottii*), blackgum (*Nyssa sylvatica*), yellow poplar (*Liriodendron tulipfera*), red maple (*Acer rubrum*), sweet bay (*Magnolia virginiana*), and red bay (*Persea borbonia*). The forests are partially flooded during early spring, with smaller streams drying up in the late summer (Fail 1983).

Procedures

Existing studies of ‘regional’ nutrient dynamics (Miller and Wolfe 1978; Robertson 1982) have concentrated on nutrients aggregated into compartments (*e.g.*, water, landuse type, soil, etc.). In this study we disaggregate the compartments using an adaptation of the Map Analysis Package (Tomlin 1980). MAP uses a conventional grid-cell structure to store digitized maps termed ‘layers’. Each layer is a map of land use, soil type, topography or other environmental variables registered over a common geographic area. The resolution of the maps is determined by the cell size. An additional consideration in this study was the size of the smaller fields and farm ponds on Watershed F; a cell size too large might miss these features. These smaller features were determined to be slightly less than 2 ha (Julie Sharpe, personal communication). As a compromise, a cell size of 1.5 ha was adopted.

The detailed methods for using MAP are presented in Kesner (1984), but can be summarized here as involving three important steps:

1. The development of a comprehensive data base in which land use and other physical and biological variables are quantified and integrated spatially.

2. The incorporation of data from previous site-specific research on nutrient cycling in LRW into the GIS; and
3. The utilization of the GIS for cartographic and mathematical manipulation of the spatial data on total nitrogen in LRW agroecosystems.

Every 1.5 ha cell of Watershed F was assumed to have inputs, outputs, and storages of nitrogen. Inputs could be accounted for in bulk precipitation (wet fall + dry fall), fertilizer applications, and biological nitrogen fixation. The major outputs from a given pixel (picture element) could be accounted for by gaseous losses (denitrification and NH_4^+ volatilization) and removal of crops by harvest. If the inputs to a pixel are greater than the outputs, it was assumed that the excess could leave through surface runoff and subsurface leachate, or be added to the perennial vegetation, if any, and soil. All data entered represent annual totals for 1981, a year during which extensive field surveys were made by USDA-ARS. This accounting procedure for nitrogen in the landscape uses land use as the primary quantitative and qualitative control of transfers and storages of N. This approach also relies heavily on past research of nitrogen cycling in the LRW. Lists of the sources for the previous work and data collected for the LRW are presented in the Appendix.

All of the component parts of the nitrogen cycle which could be reliably quantified over a wide range of land uses were first checked for accuracy, and then entered into computer files. Where it was impossible to find reliable values for a particular aspect of the N cycle on LRW, other sources from the current literature on N cycling in coastal plain environs were utilized. (Kesner 1984 gives a complete breakdown of nitrogen inputs, outputs, and storages for each land use category).

Nitrogen inputs, outputs, and storages in Little River Watershed

The simulation of regional nitrogen dynamics for 1981 in Watershed F generated by the GIS can be visualized through a series of computer generated maps. These maps depict the spatial pattern of input, output, and storage of total nitrogen as well as net balance, all expressed in kg/ha.

Nitrogen inputs

Input of total N to Watershed F from both natural and anthropogenic sources is based on the input of N per 1.5 ha pixel, *i.e.*, each print position covers an area of 1.5 ha. The majority of the watershed (53% or 6,138 ha) has N inputs of less than 40 kg/ha. A background pattern interspersed by patches of higher input, represents input from atmospheric and biological fixation. Bulk precipitation contributed approximately 12 kg/ha in 1981, while N-fixation (both symbiotic and non-symbiotic) contributed, on the average, 1 to 10 kg/ha. Although this input of 13–39 kg/ha is small when compared with that in the cultivated areas, it represents the vast majority of incoming N for the watershed. If one compares the arrangement of inputs with the location of agricultural and forest areas of the generalized land use map (not presented here) the control by the spatial pattern of land use is clearly evident.

Inputs greater than 40 kg/ha generally correspond with agricultural fields where large amounts of N-fertilizer were applied. The patches with the largest inputs are fields planted in vegetable crops (193 kg/ha), corn (181 kg/ha), peanuts (162 kg/ha), and soybeans, double cropped with winter wheat (142 kg/ha). Fertilizer applications produce the largest inputs of N per pixel to the landscape, as shown on a map of fertilizer applications (Fig. 2). Data on the amounts normally applied to individual crop types in 1981 were obtained from county agricultural extension records and interviews of farmers conducted by previous workers in the 'Tifton Project' (Lowrance *et al.* 1983, see also Appendix 1).

Nitrogen outputs

The predicted output of N for the watershed shows a much more complex pattern than inputs (Fig. 3).

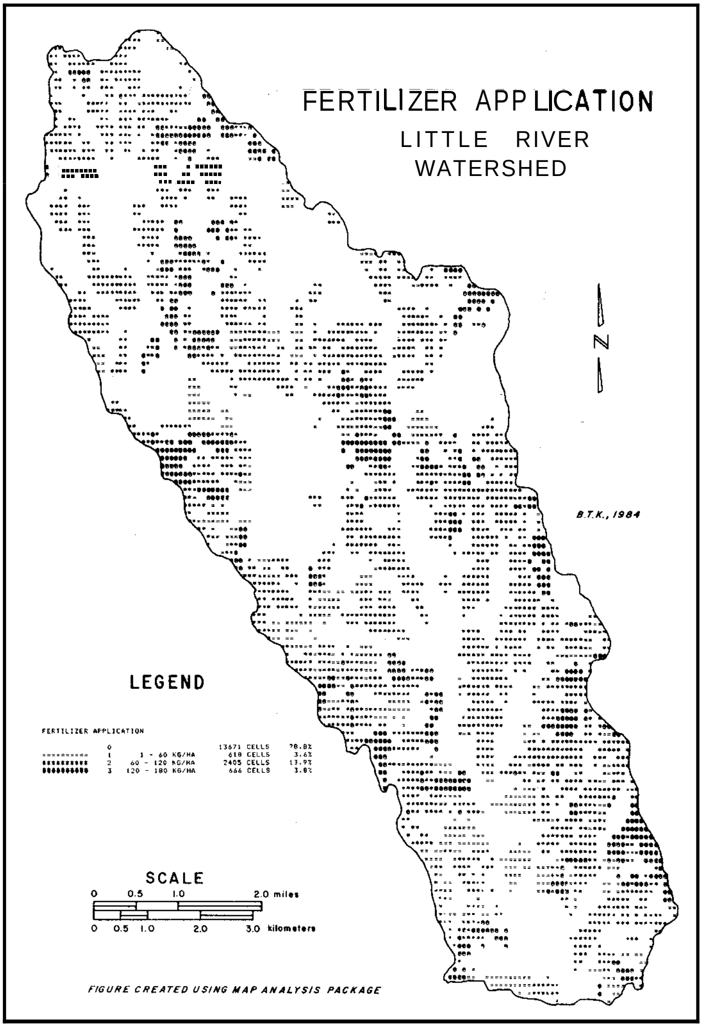


Fig. 2. Computer-generated map of N-fertilizer applications (kg/ha) on Watershed F. Each print position is equivalent to 1.5 hectares.

Nevertheless, most of the pixels in the map, *i.e.*, the background pattern (51% or 14,795 ha), have an output per cell of 1–4 kg/ha. This is attributed to gaseous loss of N through denitrification and/or ammonia volatilization, which ranges from about 1 to 34 kg/ha, depending on land cover (Kesner 1984).

The largest rates of N loss per pixel are attributed in this map to harvest from the agricultural fields. Apparently, loss of N in harvestable crop parts (*i.e.*, grain, fruits, or leafy matter) is often more than 80% of the total output per pixel in agriculture. Nitrogen in crops harvested annually ranged from 30 kg/ha for cotton, to 151 kg/ha for corn. Frissel (1978) noted these high losses of N through harvest as typical of intensive agriculture. Bellot and Golley (1989) found that harvested products represented the largest outputs of N and P for an irrigated agroecosystem in Spain. Thus the pixels in agriculture may be characterized as open systems, with very high production being maintained by the continuous supply of inorganic fertilizer.

*Net gains **and** losses of nitrogen*

The map of total output was subtracted from that of total input to create a map of net gain or loss of

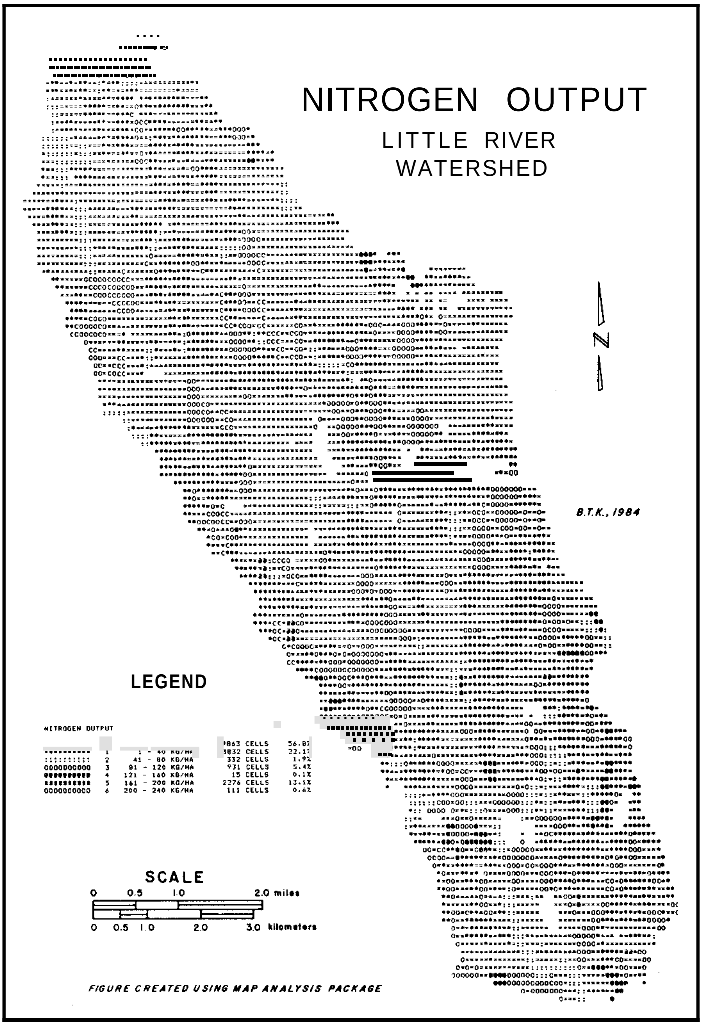


Fig. **3. Map** of **total** N **losses (export).**

nitrogen in the landscape (Fig. 4). When this map is compared with the land use map it reveals that those areas of net N surplus are generally the agricultural fields; however, some agricultural areas are shown to have a small net loss of N. Apparently, loss from harvest and removal of crops and gaseous loss was not entirely compensated for by fertilizer and other inputs, at least not in 1981. However, 1981 had slightly less than normal rainfall which could have caused less N input. Crops which have a large loss of N by harvest include tobacco, double cropped soybeans with winter wheat or rye, and fields with harvest of hay and forage.

The map of net gain or loss of N for Watershed F, illustrates some of the key attributes of the landscape and nutrient dynamics of this region. First, and foremost, there is a linkage and interaction between two seemingly dissimilar ecosystems. The riparian ecosystem is shown as an area of net loss of N, while the cultivated uplands are primarily areas of N surplus. If the available surplus from the upland cultivated areas is not considered as a subsurface (phreatic) input to the riparian ecosystem, then there is a net deficit of −22 kg/ka. The largest part of this N deficit can be attributed to the very high rate of gaseous loss in the riparian areas.

This net loss of N is further verification of the

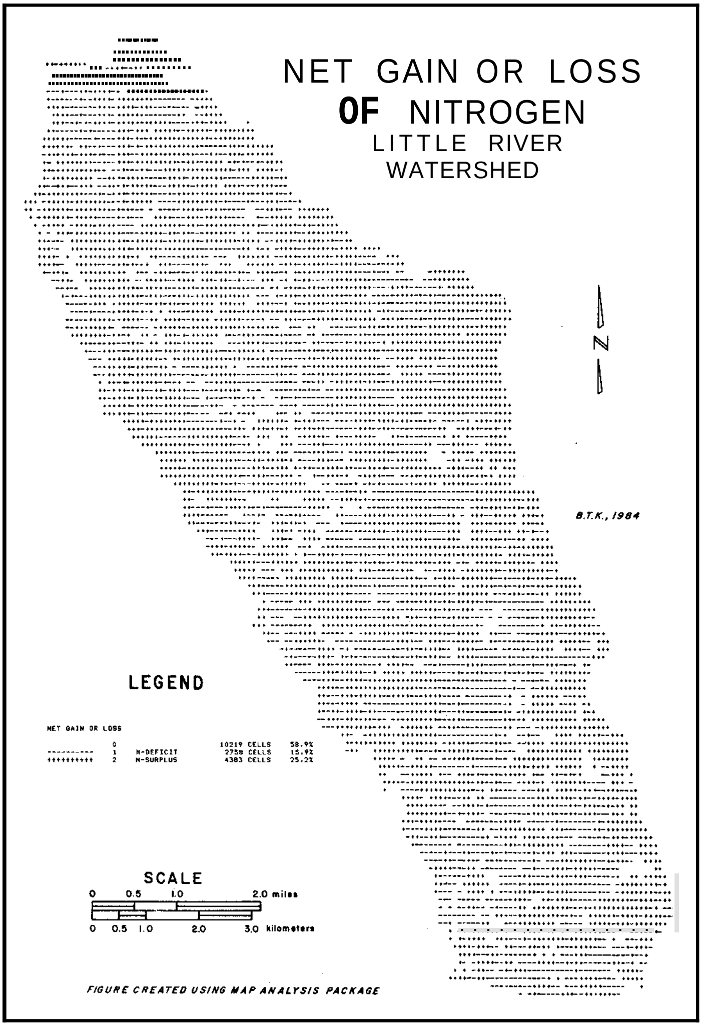


Fig. **4. Map** of **net source** (+) **and net loss** (–) **areas** of **total N based on 1.5 hectare pixels.**

riparian ecosystem's capacity to buffer nutrients (through capture by vegetation, storage in the soil, and gaseous loss) moving from the uplands to the stream channels (Lowrance *et al.* 1983; Fail 1983). Lowrance, Todd and Asmussen (1983a) estimated the available surplus of N from the uplands to average 55.6 kg/ha/yr. If all of this N is migrating downslope to the riparian ecosystem then there is more than enough N to account for our calculated deficit of −22 kg/ha. This linkage between component ecosystems also conforms with Forman's (1981) conceptual model of matrix-stream corridor interaction. **As** do Likens and Bormann (1974), Forman considers water to be the major driving force, and water and nutrients the fluxes. In this particular case, the fluxes are essentially unidirectional from the matrix to the stream corridor, at least in the short term.

Nitrogen storages

A map of total N storage for the watershed was created by adding the nitrogen in the harvest residue of annual crops to the long term storage of N in the soil and vegetation (Fig. 5). This map shows a distinctively dentritic pattern of areas with storages greater than 15,000 kg/ha caused by areas

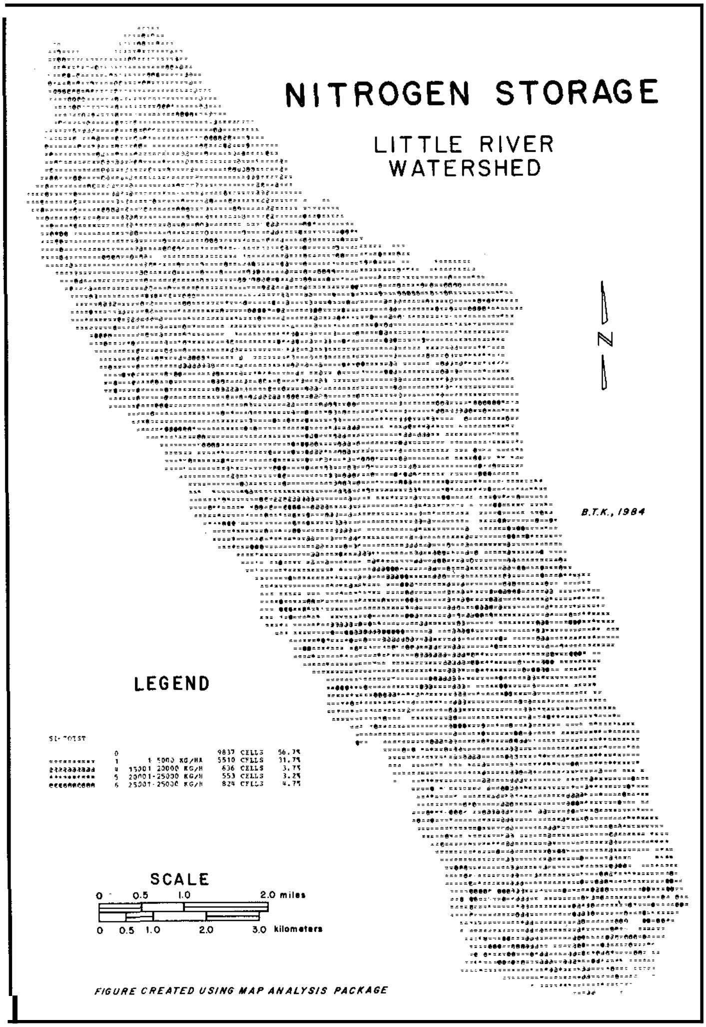


Fig. 5. Map **of** storage **of** total N in Watershed F, Little River Watershed.

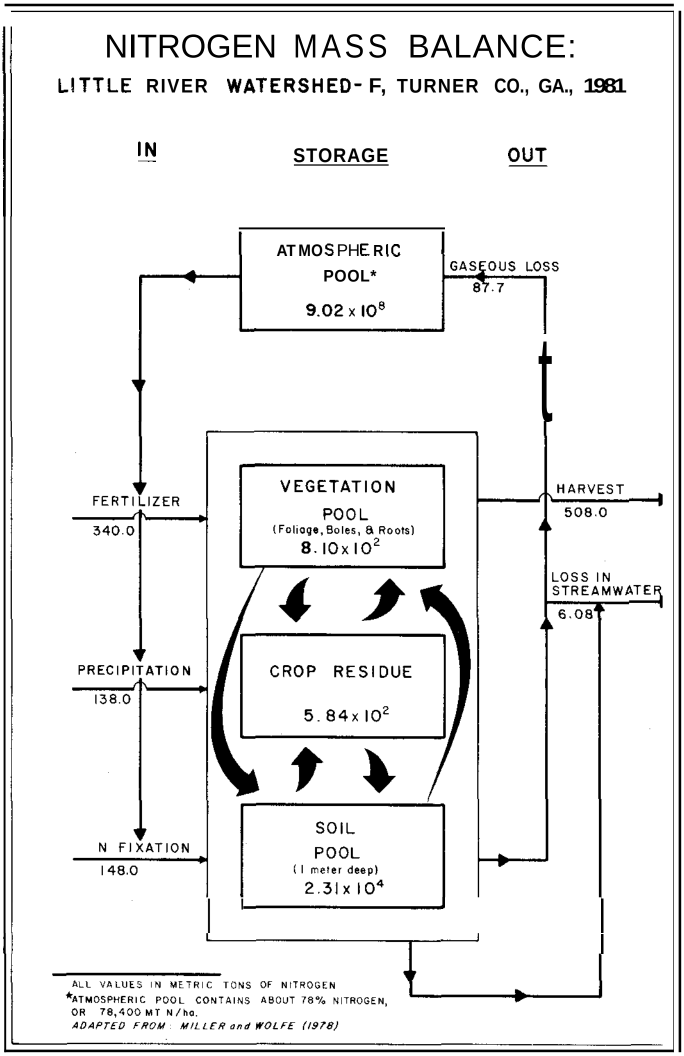
of riparian forest contiguous with the stream channels.

In the riparian ecosystem, a relatively large pool (18,000 to 24,000 kg/ha) of soil N exists versus the smaller pools of the cropped uplands. Lowrance *et* al. (1983) attribute these high soil N levels to past movement of sediment from the upland areas, the relatively high clay content of the bottomland soils (30–50% kaolinite), and the large amount of undecomposed and buried organic matter.

Total system turnover

The concept of residence time, or rate of nitrogen turnover, is useful for evaluating the dynamics of N in any ecosystem. Odum (1971) defines turnover as the ratio of throughput of a nutrient to its content. Turnover can be expressed as a rate fraction per year, or as a turnover time, which is the reciprocal of the rate fraction. Residence time, a similar concept, is the time required to replace a quantity of substance equal to the amount in the ecosystem compartment (Frissel 1978).

The spatial pattern of total system turnover for the LRW was calculated by dividing total storage of N in a cell (including the soil compartment) by total input per cell (Van Cleve and Alexander 1981). The turnover time index was then mapped (not shown



ALL VALUES IN METRIC TONS OF NITROGEN
*ATMOSPHERIC POOL CONTAINS ABOUT 78% NITROGEN, OR 78,400 MT N/ha.
ADAPTED FROM: MILLER and WOLFE (1978)

Fig. 6. Estimated amounts of total N in major storage compartments and transfers among compartments for the entire study area (Watershed F). These estimates are based on the planimetric capabilities of the Map Analysis Package (MAP).

here) to display the geographic variation of the rate of nitrogen circulation through both the vegetation and soil compartments. About 77% of the watershed (or 8,847 ha) falls in the map category of less than 334 years of mean turnover time. These areas generally correspond with both upland fields and pine plantations, with the shortest turnover times in pixels with large fertilizer applications and crop harvest. Again, the dendritic pattern which corresponds to the riparian zones appears. In this case, much slower rates of turnover for total system N occur in the riparian forests. The majority of these areas show an average turnover time of between 1,300 and 2,000 years. The high organic N of the riparian zone soils (which includes sediments and buried organic matter) and the N bound up in boles of trees account for the much longer turnover time versus that of the upland areas.

When turnover times of both upland and riparian ecosystems for LRW are compared with published values of total system turnover of N of other areas, the values are in reasonable agreement. Van Cleve and Alexander (1981) observed a general increase in turnover time of total system N with an increase in latitude. For example, the temperate deciduous forest of Hubbard Brook New Hampshire (latitude 43'56' N) has a reported turnover time of 253 years in well-drained areas. The LRW's (latitude 31'35 'N) average turnover in the upland ecosystem of 168 years fits this general pattern, considering the warmer, more humid climate.

Calculations of watershed mass balance

The planimetric capabilities of MAP were used to compile estimates of the total nitrogen input, storage, and loss for the Watershed F. Figure 6 shows estimated amounts of nitrogen in the major compartments and estimated transfer rates for a regional mass balance of the study area. These estimates are based on 1981 data for land use, hydrologic discharge, and water quality, etc. for the entire Watershed F drainage basin (11,490 ha). This mass balance scheme, adapted from Miller and Wolfe (1978) is not intended to be a complete model of nitrogen in the LRW landscape. The figure represents only the major compartments and transfers which could be estimated using the GIS. Transfers of N by animals could not be included; fortunately animal densities are fairly low on LRW. Bulk precipitation and N fixation provide the major inputs of N from the atmosphere to the land surface; although this N may not come directly from the atmosphere over Watershed F. Bulk precipitation inputs of N are approximately 12 kg/ha/yr (Lowrance 1981), which is equal to 134 MT N for the entire study area.

Hendrickson (1981) and Hoyt (1981) measured both symbiotic and non-symbiotic N-fixation for various land uses on the Little River Watershed. Fields planted to legumes (*i.e.*, soybeans and peanuts) were estimated to have fixation rates as high as 60 kg/ha/yr in 1979; other crop types and uses had measured rates varying from 1 to 40 kg/ha/yr. Moreover, strong seasonal trends were reported, with maximum activity in the spring (Hendrickson 1981). Total N fixed in 1981 in Watershed F was approximately 148 MT.

Additions to the atmospheric pool of N from the land surface and soil compartments through gaseous loss were found to vary greatly throughout the landscape, depending in large part on micro-site conditions of moisture, temperature, and organic matter content of the soil. Generally those sites having moist anaerobic, low pH soil conditions, and high organic matter content (*e.g.*, the riparian forests), experienced the largest levels of gaseous loss (22–34 kg/ha/yr). This pattern was also reported by Broadbent and Clark (1965). Upland areas have somewhat lower estimated rates of gaseous loss, ranging from 5–15 kg/ha/yr (Hoyt 1981; Hendrickson 1981). Total gaseous loss in Watershed F is estimated at 87.7 MT.

As mentioned previously, N fertilizers are the major cultural input of N to this agricultural landscape. In 1981, total application in Watershed F was about 340 MT. This amounts to 54% of total N input for this watershed. Based on the compounds mixed to produce fertilizers in the area, 98% of the fertilizer applied was estimated to be NH_4-N (Lowrance *et al.* 1983). The estimated losses in harvested materials are also large, about 508 MT, or 85% of the total output.

The storage pool of N in the vegetation compartment (810 MT) was estimated by summing the storage of N pools for roots, tree boles, and leaf biomass of perennial vegetation. These storages are, for the most part, long term and do not change appreciably except for major modifications of land use (*e.g*, land clearing for agriculture and succession following clearing and abandonment).

Crop residues represent an addition pool, which for the whole watershed, is estimated to be about 584 MT. The bulk of this residue is incorporated into the soil N pool, usually within the year because of rapid rates of mineralization. The residues also add organic matter, which is important for improving the physical characteristics and water-holding capacity of the soil (Brady 1974).

Total N storage for a 1 ha × 1 m deep layer of soil was calculated by multiplying percent N content by bulk density (measured as g/cm^3), for each Family of soils, and summing the values for total storage using the GIS. Total storage of N in Watershed F is estimated at 2.31×10^4 MT. The storage of N in the geologic substrate is essentially ignored in this and previous nitrogen cycling studies of the LRW. Because N is essentially absent from the bedrock at LRW, an assumption was made that the release of nitrogenous substances by weathering and the formation of secondary nitrogenous minerals are negligible, especially when compared with inputs from precipitation or N-fixation (Lowrance 1983, personal communications; Likens *et* al. 1977). Total storage in the terrestrial component (vegetation and soil for Watershed F) is estimated at 2.39 x 10^4 MT.

Nitrogen accumulation in the landscape

As a final step in understanding the implications of this geographic approach to estimate mass balance of N in the LRW landscape, comparisons were made between total inputs and outputs, and the N measured at the Watershed F gauging station. By subtracting total output from the total input, a net surplus of 30 MT results. Records of total N load at Watershed F gauging station indicate that for 1981, an average of 0.529 kg/ha/yr, or a total of 6.08 MT left the watershed in stream water (Sharpe, 1983, personal communications). After this value is subtracted from the net surplus (30), there is still a small net gain of 24 MT of total N accumulated in the LRW landscape in 1981.

There is, of course, no good means to determine exactly the net gains or losses of N by the entire watershed. We could not, for example, account for denitrification and gaseous losses in the stream. There is good evidence, however, that the riparian forests are a sink for N lost from the upland fields (Fail 1983; Hamah 1983; Lowrance 1981). Fail (1983) reported an average annual accretion rate of 40 kg/ha/yr for the LRW riparian forest. Multiplying this rate of accretion by the estimated 1972.0 ha of riparian forest in watershed F gives a total of approximately 78.9 MT of N accreted. The amount of net N surplus in Watershed F **(30** MT) calculated in the present study using the GIS, also points to net accretion in riparian forests.

It is feasible that some of this surplus is also added to the soil storage and stream sediments. The only way of verifying such hypotheses is through further field research. Besides the possibility of accretion into riparian vegetation or storage in the soil N pool, there is also some uncertainty as to the accuracy of measurements and estimates for gaseous loss of N. Many of the differences in estimates of surplus N between this and previous studies in the 'Tifton Project' can be explained by the differences in methodology.

Conclusion

This study has presented the results of an application of a Geographic Information System to the problem of assessing spatial variation in nitrogen mass balance. The maps of total N dynamics in an agricultural landscape presented here, show great spatial variability and the strong control by landuse on spatial patterns of input, export, storage and turnover of elements. The study also demonstrates the use of the planimetric capabilities of a GIS to produce alternative estimates of the mass balance for entire watersheds. These estimates confirm the results of previous work which shows that landscapes in the Little River Watershed of southern Georgia are remarkably well buffered against losses of N in spite of large applications of N-fertilizers. It is clear, however, that this approach and the estimates it yields are only as good as the estimates and measurements of N balance on which it is based. No doubt errors are present, especially for the smaller or unusual landuse classes. Estimates of N in harvests and crop residues for some of these classes (*e.g.*, tobacco) were particularly difficult to determine. Nevertheless, the spatial patterns and estimates of N balance for the entire watershed should not be severely biased. Hopefully this study represents a step toward the development of holistic, spatial models of nutrient dynamics in landscapes.

Acknowledgments

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Appendix 1

Parameters measured, methodology, and referenced sources of the Tifton agricultural watershed project[1]

Parameter	Methods	Reference
Upland ecosystem		
Upland agronomic inputs/outputs	Land use surveys, farmer interviews, average fertilizer & harvest rates. Experimental plots for corn, peanuts and soybean	Lowrance ***et al.*** 1985, Hoyt 1981
Above-ground plant N	Monthly sampling of experimental plots	Hoyt 1981
Below-ground plant N	Monthly sampling of experimental plots	Hoyt 1981
Litter standing crop and decomposition	Monthly sampling of experimental plots; litter	Hoyt 1981; Hice 1981
Organic & inorganic soil N pools	Monthly sampling of experimental plots; the extraction or digestion & N analysis	Hoyt 1981
Symbiotic N – fixation	Estimates based on soybean & peanut yield	Hoyt 1981; Kvien, pers. commun.
Non-symbiotic N-fixation	C_2H_2 analysis by gras chromatography	Hoyt 1981
Precipitation inputs	Standard rain gauges & collectors for bulk precip.	Lowrance ***et al.*** 1985
Phreatic pools & transfer from upland to riparian zone	Periodic sampling of wells for N concentrations; water balance to estimate water movement	Lowrance 1981; Lowrance ***et al.*** 1983
Riparian ecosystem		
Throughfall/precipitation	Collection from fixed samplers & N analysis	Lowrance 981
Litterfall	Monthly collection, microkjeldahl digestion	Lowrance 981
Above-ground vegetation uptake & accrual	Determination of community structure; increment boring, vegetation sampling & subsampling; N analysis	Fail 1983
Below-ground vegetation uptake & accrual	Periodic sampling of large & fine root biomass, N – analysis	Hamzeh 1983
Below-ground litter decomposition	Soil block method; N – analysis	Hamzeh 1983
Above-ground litter decomposition	Litter bags, sampling of forest floor standing crop	Walther 1983; Lowrance 1983
Organic & inorganic soil N pool	Periodic sampling, extraction or digestion & N analysis	Hendrickson 1981; Hamzeh 1983
Non-symbiotic N-fixation	C_2H_2 reduction & C_2H_2 analysis by gas chromatography	Hendrickson 1981
Symbiotic N-fixation	Estimates of Permar and Risher 1982	Hendrickson 1981
Microbial denitrification	C_2H_2 block & N_2O analysis by gas chromatography	Hendrickson 1981
N_2O evolution by nitrifying bacteria	Gas chromatography	Hendrickson 1981
Streamflow nutrient loads	Twice daily sampling & integration of concentration & discharge analysis	Lowrance ***et al.*** 1985

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[1] Adapted from Lowrance ***et al.*** 1983.