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Temporal and spatial trends in nitrogen and phosphorus inputs to the watershed of the Altamaha River, Georgia, USA

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Abstract The watershed of the Altamaha River, Georgia, is one of the largest in the southeastern U.S., draining 36,718 km^2 (including parts of metro Atlanta). We calculated both nitrogen (fertilizer, net food and feed import, atmospheric deposition, and biological N fixation in agricultural and forest lands) and phosphorus (fertilizer and net food and feed import) inputs to the watershed for 6 time points between 1954 and 2002. Total nitrogen inputs rose from 1,952 kg N $km^{-2}\,yr^{-1}$ in 1954 to a peak of 3,593 kg N $km^{-2}\,yr^{-1}$ in 1982 and then declined to 2,582 kg N $km^{-2}\,yr^{-1}$ by 2002. Phosphorus inputs rose from 409 kg P $km^{-2}\,yr^{-1}$ in 1954 to 532 kg P $km^{-2}\,yr^{-1}$ in 1974 before declining to 412 kg P $km^{-2}\,yr^{-1}$ in 2002. Fertilizer tended to be the most important input of both N and P to the watershed, although net food and feed import increased in importance over time and was the dominant source of N input by 2002. When considered on an individual basis, fertilizer input tended to be highest in the middle portions of the watershed (Little and Lower Ocmulgee and Lower Oconee sub-watersheds) whereas net food and feed imports were highest in the upper reaches (Upper Oconee and Upper Ocmulgee sub-watersheds). Although the overall trend in recent years has been towards decreases in both N and P inputs, these trends may be offset due to continuing increases in animal and human populations.

Keywords Altamaha River · Nitrogen budgets · Nutrient inputs · Phosphorus budgets · Spatial distribution · Temporal trends

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Introduction

Inputs of reactive nitrogen (N) and phosphorus (P) to global cycles have increased dramatically as a result of anthropogenic activity. Total reactive nitrogen inputs into the global system increased from 15.6 Tg yr^{-1} to 139 Tg yr^{-1} between 1890 and 1990 as the result of changing agricultural practices (increases in biological nitrogen fixation and fertilizer production as well as emissions from fossil fuel use; Galloway and Cowling 2002). By 2050, these inputs are expected to reach 270 Tg yr^{-1} (Galloway et al. 2004). Human alterations to the global phosphorus cycle are a result of the intensification of erosion, point source inputs from major cities, and the application of fertilizers (both organic and inorganic) (Smil 2000). As a consequence of these activities, P mobilization on a global scale has increased between 2.5 and 5-fold over natural background values (Howarth et al. 1995; Smil 2000; Bennett et al. 2001). Since the P cycle is controlled primarily by geological processes, this mobilization cannot be reversed on human time scales (Schlesinger 1997; Smil 2000).

In the United States, both nitrogen and phosphorus inputs have increased over the last half century. Reactive N inputs have doubled since 1961, mostly due to increases in the 1960s and 1970s (Howarth et al. 2002). The most important source of N in the 1960s was agricultural N fixation, but inputs from fertilizer and atmospheric deposition are now both more important (Howarth et al. 2002). The use of N fertilizers increased by a factor of approximately 20 since the middle of the last century (Alexander and Smith 1990). Changes in P have not been as well-studied, but P fertilizers increased by a factor of approximately five over the same time period (Alexander and Smith 1990).

Trends in nutrient inputs have been well-documented at the watershed scale. Bowen and Valiela (2001) reported a 67% increase in nitrogen input to the watershed of Waquoit Bay, MA between 1938 and 1990. In the watershed of the Neuse River, NC, Stow et al. (2000) found that both N and P inputs have increased since the 1950s (although N and P inputs from cropland sources both reached peaks in the late 1970s). N inputs to the watershed of the Mississippi River increased from 10.4 to 17.3 kg N ha^{-1} yr^{-1} between the 1950s and 1990s, with much of the increase taking place in the 1960s (McIsaac et al. 2002).

Although these studies provide estimates of nutrient inputs to whole watersheds, the spatial patterns of these inputs is also important. Models of N and P delivery to rivers draining to the Chesapeake Bay have found that inputs are often concentrated near the bottom of the watersheds (Sprague et al. 2000). Liu et al. (2006) found that N sources expanded from near cities to more rural areas in China between 1980 and 2000, and that an increase in fertilizer usage was primarily responsible for these increases. This type of information is useful for interpreting spatial patterns of instream nutrient concentrations as well as for identifying appropriate targets for nutrient management.

The Altamaha River is formed by the confluence of the Oconee and Ocmulgee Rivers. The watershed is one of the largest on the east coast of the United States, encompassing an area of 36,718 km^2 and draining 24% of the state of Georgia, including parts of metro Atlanta (Fig. 1). Southeastern U.S. rivers and streams have some of the world's highest biodiversity (Olson and Dinerstein 1998) and a high percentage of the mussels found in the Altamaha River are endemic to the system (Wisniewski et al. 2005). The river remains undammed, and has been the focus of a watershed-scale conservation effort through The Nature Conservancy's Altamaha Bioreserve project. Previous studies of nutrient inputs to the Altamaha River watershed reported inputs to be dominated by agricultural sources (Asbury and Oaksford 1997; Castro et al. 2003; Schaefer and Alber 2007). These studies, which all focused on recent conditions, reported a range of 2,830–5,470 kg N km^{-2} yr^{-1}. There has been only one previous estimate of P input (1,380 kg P km^{-2} yr^{-1}; Asbury and Oaksford 1997). However, neither changes in inputs to the watershed over time nor their spatial distribution have been examined.

There have been numerous changes in Georgia since the 1950s. The population of the state increased from 3.4 million to 8.2 million in 2000 (Forstall 1995; USBoC 2000). At the same time, agricultural practices also changed: national shifts in farming practices since the 1950s caused agriculture to become more industrialized, with farmland distributed among fewer owners (Centner 2001, 2003). Between 1970 and 1990 the average population density in the watershed increased from 35 persons km^{-2} to 70 persons km^{-2} and agricultural land declined by about one third (Weston 2005). These trends most likely resulted in changes in both the amount and pattern of nutrient loading to the Altamaha watershed.

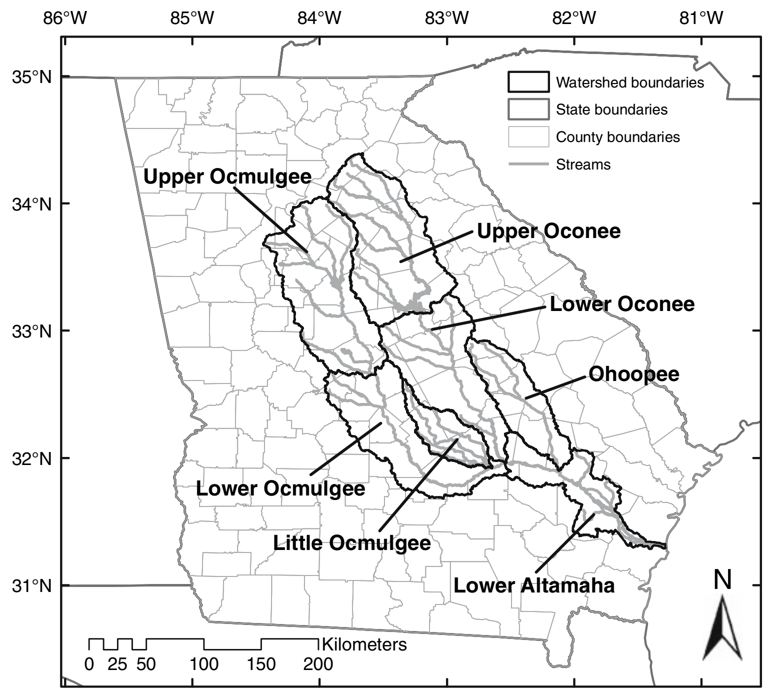
This study estimated N and P inputs to the watershed of the Altamaha River. Complete nutrient budgets were constructed for six target years: 1954, 1964, 1974, 1982, 1992, and 2002, in order to determine the temporal changes in inputs of both nutrients. Budgets were also partitioned by sub-watershed to evaluate the spatial patterns of inputs.

Methods

Watershed delineation

A GIS shapefile of the greater Altamaha River watershed and its major sub-watersheds (the Upper and Lower Oconee River; the Upper, Lower, and Little Ocmulgee River; the Ohoopee River; and the Lower Altamaha River) was obtained from the Georgia GIS Clearinghouse (McFadden 2000). Many of the data

Fig. 1 Location of the greater Altamaha River watershed and its major sub-watersheds within Georgia, USA



sets used in this study were available on a county-by-county basis, so we also determined the fraction of each county located inside the watershed. Shapefiles of the counties in Georgia were obtained from the TIGER geographic database of the U.S. Bureau of the Census (USBoC 2005) and overlaid onto that of the watershed to determine the relative proportion of each county in the watershed.

Nutrient budgets

The methodology for determining total nitrogen inputs over time is similar to that used in the International Scope Nitrogen Project by Boyer et al. (2002). Total nutrient inputs were calculated by summing all external sources of nutrients to the watershed. N inputs include fertilizer, net food and feed import, atmospheric deposition, and biological nitrogen fixation by crops and forest lands. Atmospheric deposition is only a minor source of phosphorus and there is no mechanism equivalent to biological nitrogen fixation for this element, so the only inputs of P in our budget are fertilizer and net food and feed import. Calculations for sub-watersheds were done in the same manner as those for the overall Altamaha budgets. It should be noted that a precise estimate of the error in these budgets is not possible and may be quite large, given that there are sources of error in each of the factors that go into the overall estimate. However, since all budgets were constructed in a consistent manner, the spatial and temporal trends presented here should hold even if the absolute estimates are somewhat uncertain.

Fertilizer

Published estimates of county-by-county commercial nitrogen (as N) and phosphorus (as P or P_2O_5) fertilizer sales cover the period from 1945 to 2001 (Alexander and Smith 1990; Battaglin and Goolsby 1994; Ruddy et al. 2006). We weighted the annual amount of N and P fertilizer sold in each county by the proportion of the county inside the Altamaha watershed. (In the case of P, where P_2O_5 fertilizer was reported, the weight was adjusted to reflect only the element P.) This method assumes that all fertilizer sold within a county is actually used in that same county, which may not be true in all cases. We used 1954, 1964, 1974, 1982 (Alexander and Smith 1990), 1992, and 2001 (Ruddy et al. 2006) estimates for the nutrient budgets.

Net food and feed import

Net food and feed import refers to the total amount of nutrients in food and feed that must be imported into a watershed to sustain the human and animal populations within that watershed; i.e. the quantity of food and feed needed above and beyond that which is already produced in the watershed. It requires estimates of both crop and animal production and animal and human consumption.

Information on animal populations and crops grown in each county was obtained from the USDA Census of Agriculture (USBoC 1956–1984; USDA-NASS 1987–2002) and adjusted for the proportion in the watershed. Data for each nutrient budget were taken from the corresponding census year (1954, 1964, 1974, 1982, 1992, and 2002). For this study, only crops comprising 1% or more of harvested cropland were considered. Crop data for all but pastureland and non-alfalfa hay were multiplied by N and P conversion factors obtained from the USDA PLANTS database (USDA/NRCS 2005). N content for pastureland and non-alfalfa hay is from Lander and Moffitt (1996, cited in Boyer et al. 2002) (Table 1). P conversion factors were not available for pastureland and non-alfalfa hay, but P content averaged 15% of N content for other crops so we used this to estimate P content for these two crops.

Animal consumption was estimated by multiplying populations by published annual per capita N and P consumption rates (Van Horn 1998; Tables 2, 3). To calculate animal production, livestock populations were multiplied by annual excretion rates (Van Horn 1998; Tables 2, 3) and the difference between livestock consumption and excretion in manure was assumed to constitute animal production. Following Boyer et al. (2002), 10% was subtracted from crop (excluding hay, forage, and silage crops) and animal production to account for spoilage and inedible parts.

Human population data were obtained from the U.S. Bureau of the Census for decennial censuses between 1950 and 2000 (Forstall 1995) and adjusted for proportion of each county in the watershed. Population figures used in the 1954 through 1992 budgets were estimated by linear interpolations between the census preceding and following target years. Since the 2010 census has not yet been conducted, we estimated the 2002 population from the 2000 census by applying the rate of population increase observed during the 1990s. Human consumption was estimated by multiplying the population by annual per capita consumption rates of 5 kg N yr^{-1} (Garrow et al. 2000) and 0.55 kg P yr^{-1} (Smil 2000).

Table 1 N and P crop conversion factors used in this study

Crop	lb N/unit	lb P/unit
Cotton	0.0304/lb of seed and lint	0.0038/lb of seed and lint
Corn (grain)	0.7929/bushel	0.1514/bushel
Corn (silage)	7.7501/ton	2.2644/ton
Cropland used only for pasture	2000/acre	300/acre
Non-crop pastureland	1000/acre	150/acre
Hay, alfalfa	55.7759/ton	5.226/ton
Hay, non-alfalfa	21.7/ton	3.255/ton
Oats (grain)	0.5984/bushel	0.1092/bushel
Peanuts	0.0448/lb of seed	0.0037/lb of seed
Sorghums (grain)	0.98/bushel	0.0006/bushel
Soybeans (beans)	0.0144/bushel	0.0006/bushel
Soybeans (hay)	45.9418/ton	4.3312/ton
Rye	1.0557/bushel	0.1873/bushel
Peaches	0.0012/lb of fruit	0.0001/lb of fruit
Pecans	0.238/lb of nut	0/lb of nut
Peanuts (hay)	0.0448/lb of seed	0.0037/lb of seed
Peanuts (seed)	31.743/ton	3.3931/ton
Tobacco	1.7064/hundred weight	0.218/hundred weight
Wheat (grain)	1.4366/bushel	0.2309/bushel

Sources: USDA PLANTS database (USDA/NRCS 2005) and Lander and Moffitt (1996) (pastureland and non-alfalfa hay)

Table 2 Animal N consumption and excretion rates used in this study

Animal	N consumption rates (kg $animal^{-1}$ yr^{-1})	N excretion rates (kg $animal^{-1}$ yr^{-1})
Cattle, beef	66.75	58.51
Cattle, dairy	156.00	121.00
Cattle, young	Same as adult	Same as adult
Chickens (broilers)	0.13	0.07
Chickens (layers)	0.84	0.55
Pigs & hogs	8.51	5.84
Turkeys	0.62	0.62
Horses	44.80	40.00
Sheep	5.97	5.00
Goats	5.97	5.00

Source: Van Horn (1998)

Table 3 Animal P consumption and excretion rates used in this study

Animal	P consumption rates (kg animal^{-1} yr^{-1})	P excretion rates (kg animal^{-1} yr^{-1})
Cattle, beef	13.91	10.43
Cattle, dairy	39.73	29.48
Cattle, young	Same as adult	Same as adult
Chickens (broilers)	0.02	0.01
Chickens (layers)	0.21	0.17
Pigs & hogs	1.77	0.94
Turkeys	0.15	0.09

Source: Van Horn (1998)

Net atmospheric N deposition

Information on inorganic N deposition (in kilograms per hectare) in the 1990s and 2000s was calculated from observations of the National Atmospheric Deposition Program (NADP) and Clean Air Status and Trends Network (CASTNET) (NADP 2006; USEPA 2006) for wet and dry deposition, respectively. In each case, stations in and around the Altamaha were used.

For 1992, inorganic N deposition values for each station were averaged for all years between 1987 and 1996 (the decade bracketing the target year of 1992) for which data were available. For 2002, years between 1997 and 2005 were used. We chose to bracket these estimates because data at both NADP and CASTNET stations were incomplete or altogether missing frequently enough that focusing exclusively on the target year would have severely limited the number of stations available for our estimates. There was very little year-to-year variation in either wet or dry deposition measurements at stations for which there was complete coverage, suggesting that the use of averaged data for this term was not a large source of error. These stations were used to interpolate grids of regional atmospheric N deposition by kriging in a GIS (ordinary linear kriging, 200 m pixel size) (ESRI 2004). The grids were then clipped to the watershed extent and averages calculated. Organic N deposition has been observed to be 30% of total atmospheric deposition (reviewed in Neff et al. 2002), so we added 30% to the sum of inorganic wet and dry deposition in order to obtain total atmospheric deposition.

Historic data on inorganic N deposition were not available from the NADP and CASTNET programs, neither of which were established until the late 1970s or 1980s. In order to hindcast, we used information on nationwide changes in NO_X emissions compiled by the U.S. Environmental Protection Agency (USEPA 2000). We assumed that the Georgia temporal trend was the same as the nationwide trend and that the proportion of nationwide atmospheric N emissions deposited in the Altamaha watershed remained constant. We calculated the ratio of 1987–1996 inorganic atmospheric deposition in the Altamaha watershed to 1987–1996 nationwide emission, and multiplied 1954, 1964, and 1974 national emissions estimates by this ratio. For the 1982 budget, there were sufficient data from the NADP network to allow us to calculate wet deposition using values between 1979 and 1986. 1982 dry deposition was estimated using the hindcasting technique described previously, using the ratio of 1987–1996 dry deposition to total nationwide emissions. These numbers were again increased by 30% to account for organic N deposition.

Not all of the N contained in the total atmospheric deposition number represents new N to the watershed, and there is some danger of double-counting inputs if N is generated locally. In order to account for this, we followed the methodology of Boyer et al. (2002) and made several adjustments to total deposition in order to estimate net atmospheric deposition for use in the budget (Table 5). First, only half of the estimated organic deposition was assumed to constitute a new input to the watershed. Second, some of the NH_4 in atmospheric deposition is likely to come from volatilization of animal waste or fertilizer that originated in the watershed. The NADP and CASTNET monitoring stations are generally well-removed from agricultural areas and are therefore unlikely to capture most local deposition, but we assumed that 25% of each emission (fertilizer and manure) was transported long-range and therefore must be subtracted from total atmospheric deposition (Boyer et al. 2002).

To calculate volatilization from fertilizer, we used 1954, 1964, 1974, 1982 (Alexander and Smith 1990), 1992, and 2001 (Ruddy et al. 2006) estimates of fertilizer sales to calculate volatilization losses as a percentage of the different types of N found in fertilizer. 1985–1991 fertilizer data (Battaglin and Goolsby 1994, see above) were broken down by type of N fertilizer (urea, ammonium nitrate, nitrogen

Table 4 Rates of biological nitrogen fixation used in this study

Crop	kg N km^{-2} yr^{-1}	Reference(s)
Hay, alfalfa	22,400	Heichel et al. (1984)
Hay, non-alfalfa	11,700	Lander and Moffitt (1996, cited in Boyer et al. 2002)
Pastureland, all types	1,500	Jordan and Weller (1996)
Peanuts	8,000	Smil (1999)
Soybeans	9,600	Average of published values, after Boyer et al. (2002)

solutions, anhydrous ammonia, and other combined fertilizers). Earlier and later data (Alexander and Smith 1990; Ruddy et al. 2006) did not include information on types of N fertilizer, so we assumed that the proportion of total fertilizer sales represented by each type of fertilizer was the same as in 1991. We used loss factors reported by Battye et al. (1994) for each type of N fertilizer to estimate total volatilization. To calculate emissions from animal manure, ammonia emission rates reported in kg N $animal^{-1}$ yr^{-1} (Battye et al. 1994) were multiplied by the total number of animals in the watershed (see Net Food and Feed Import).

Nitrogen fixation

Biological N fixation for each budget was calculated based on crop distributions obtained for the corresponding year in the Census of Agriculture (USBoC 1956–1984; USDA-NASS 1992–2002). The area of each nitrogen-fixing crop was weighted by the proportion of the county inside the Altamaha watershed and total crop acreages were multiplied by published N fixation rates (Table 4).

Biological nitrogen fixation in forestlands was also calculated for each time point. Non-symbiotic N fixation was assumed to be 40 kg N km^{-2} yr^{-1}, following Boyer et al. (2002). Forestland area for the 2002 budget was calculated using the Forest Inventory and Analysis (FIA) database (USDA-FS 2005) (using the Georgia inventory done in 2003, which was the closest year available). 1992 values were calculated using the 1989 Georgia inventory. Since the FIA program was not yet in place before that time, we used 1985 and 1974 land cover data (NARSAL 2003a, b) to calculate forested area and non-symbiotic N fixation for, respectively, the 1982 and 1974 budgets. Land cover data were not available for 1954 or 1964, and thus we were unable to estimate forested land at these points in time. Therefore, we used 1974 data for these time points.

Following the methodology of Boyer et al. (2002), we also considered symbiotic N fixation in forestlands. Black locust was assumed to make up 10% of oak-hickory stands (Boyer et al. 2002). We used a symbiotic nitrogen fixation rate of 5,000 kg N km^{-2} yr^{-1} (Boring and Swank 1984) for this tree species. Oak-hickory stand area reported in the FIA database was used for the 1992 and 2002 time points. We assumed that the proportion of forested area consisting of oak-hickory stands did not change between 1992 and earlier years and thereby calculated symbiotic N fixation by black locust using 1985 and 1974 land cover data (NARSAL 2003a, b). The 1974 figure was also substituted in the 1954 and 1964 budgets.

Land cover data were also used to estimate biological N fixation by alders, another symbiotically fixing tree species. 1998 Georgia GAP land cover data (Kramer et al. 2003) classified shrub wetlands as those dominated by willows, alders, and red maple. We assumed alder to cover 50% of shrub wetland area and to have a fixation rate of 4,000 kg N km^{-2} yr^{-1} (Hurd et al. 2001), and used this figure for the 2002 budget. This may be an overestimate, but is smaller than and most likely closer to the true value than the 10% of total wetland area used by Boyer et al. (2002). We used the proportion of forested wetland made up of shrub wetland in 1998 to estimate alder N fixation for the 1992, 1982, and 1974 budgets, as the land cover data used for these time points (USGS 1999, NARSAL 2003a, b) did not separate shrub wetlands from other types of wetlands. Since no land cover information was available for 1954 or 1964, we again used 1974 data as a placeholder.

Our use of 1974 forest N fixation data in the 1954 and 1964 budgets is clearly a potential source of error. However, forest N fixation was a small component of the overall inputs (generally less than 5%), and thus the budgets are not substantially affected by this substitution. In addition, biological N fixation inputs from the invasive leguminous vine kudzu (genus *Pueraria*) were not included in these budgets and could represent a substantial additional N input (Schaefer

Table 5 Nitrogen inputs to the Altamaha watershed in 1954, 1964, 1974, 1982, 1992, and 2002

	1954	1964	1974	1982	1992	2002
Fertilizer	503	996	1,618	1,405	1,012	695
Net atmospheric N deposition	251	335	532	461	535	401
Total atmospheric deposition	390	530	562	762	815	814
Organic N adjustment	(58)	(80)	(115)	(114)	(122)	(122)
Fertilizer volatilization	(3)	(6)	(10)	(8)	(6)	(4)
Manure volatilization	(77)	(110)	(109)	(178)	(152)	(288)
Total biological N fixation	734	601	797	1,007	657	496
Crop biological fixation	644	511	707	918	552	438
Forest non-symbiotic BNF	20	20	20	21	26	27
Locust fixation	53	53	53	53	68	18
Alder fixation	17	17	17	15	11	14
Total forest fixation	91	91	91	89	105	59
Net food and feed import	495	541	579	726	736	1,030
Crop production	(807)	(704)	(872)	(766)	(670)	(546)
Animal production	(274)	(287)	(339)	(405)	(401)	(517)
Animal consumption	1,457	1,387	1,609	1,685	1,544	1,752
Human consumption	119	145	180	212	264	340
Non-food crop export	(31)	(382)	(22)	(7)	(21)	(41)
Total N input	1,952	2,091	3,505	3,593	2,918	2,582

All numbers in kg N km^{-2} yr^{-1}

2006). These budgets should be adjusted if N fixation rates for the species prevalent in the southeastern United States (*Pueraria montana var. lobata*) become available.

Non-food crop export

Cotton and tobacco are two crops grown in the Altamaha watershed that are consumed by neither humans nor animals. We assumed that virtually all of these crops are harvested for sale elsewhere and therefore subtracted their N and P production from the total inputs.

Results

Temporal trends

Nitrogen inputs to the Altamaha watershed showed an overall increase between 1954 and 2002, from 1,952 to 2,582 kg N km^{-2} yr^{-1}. Inputs of N were actually highest, at 3,593 kg N km^{-2} yr^{-1}, in 1982 and then declined by 2002 (Table 5). Total phosphorus inputs showed an increase between 1954 and 1974, rising from 409 to 532 kg P km^{-2} yr^{-1}. By 2002, however, P inputs had decreased to near-1954 levels (412 kg P km^{-2} yr^{-1}; Table 6). Below, we examine temporal trends in each component of the nutrient budgets.

Fertilizer

The amount of fertilizer N sold in the watershed increased steadily between 1954 (503 kg N km^{-2} yr^{-1}) and 1977 (1,996 kg N km^{-2} yr^{-1}) and then declined to 695 kg N km^{-2} yr^{-1} in 2001, the last year for which data were available (Fig. 2). This was in contrast to the U.S. as a whole, where N fertilizer use in 1999 was higher than in the late 1970s (Howarth et al. 2002). Sales of fertilizer phosphorus followed a pattern similar to that of N, increasing from 274 kg P km^{-2} yr^{-1} in 1954 to 450 kg P km^{-2} yr^{-1} in 1977 before falling back to 229 kg P km^{-2} yr^{-1} by 2001 (Fig. 2).

Table 6 Phosphorus inputs to the Altamaha watershed in 1954, 1964, 1974, 1982, 1992, and 2002

	1954	1964	1974	1982	1992	2002
Fertilizer	274	311	382	268	250	229
Net food and feed import	139	137	150	168	156	189
Crop production	(122)	(107)	(124)	(113)	(96)	(75)
Animal production	(80)	(78)	(89)	(96)	(89)	(105)
Animal consumption	328	306	344	354	312	331
Human consumption	13	16	20	23	29	37
Non-food crop export	(4)	(49)	(1)	(1)	(3)	(5)
Total P input	409	398	532	435	403	412

All numbers in kg P km^{-2} yr^{-1}

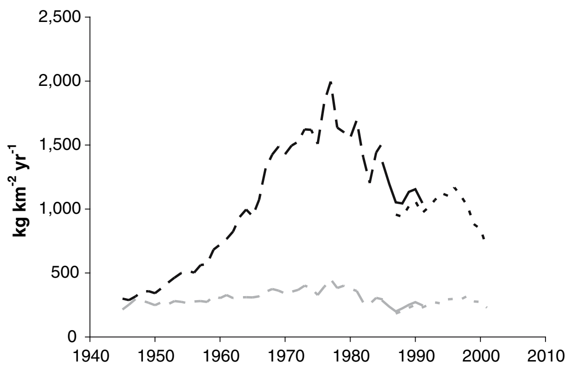


Fig. 2 Commercial nitrogen (black) and phosphorus (gray) fertilizer use in the Altamaha watershed from 1945 to 2001. 1945–1985 data (*dashed line*) from Alexander and Smith (1990), 1985–1991 data (*solid line*) from Battaglin and Goolsby (1994), and 1987–2001 data (*dotted line*) from Ruddy et al. (2006)

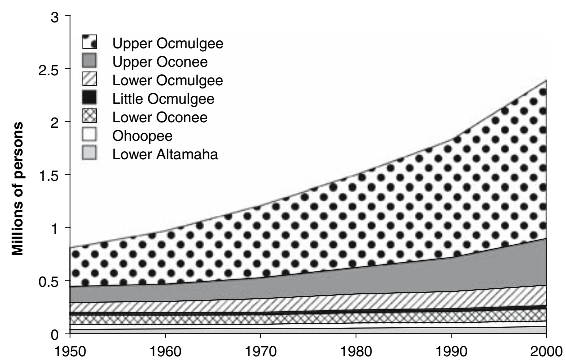


Fig. 3 Human population in the Altamaha watershed, 1950–2000. Data are broken down by sub-watershed. *Source*: United States decennial censuses (Forstall 1995; USBoC 2005)

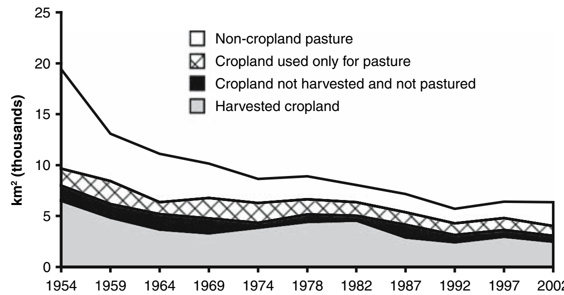


Fig. 4 Area of land in agricultural production in the Altamaha watershed, 1954–2002. Data are broken down by type. *Source*: U.S. Bureau of the Census and USDA Agricultural Censuses, 1954–2002

Net food and feed import

Net N and P import in food and feed also increased over time: between 1954 and 2002, import of N rose from 495 to 1,030 kg N km^{-2} yr^{-1} and that of P rose from 139 to 189 kg P km^{-2} yr^{-1} (Tables 5 and 6). These changes are the result of the increasing human population in the watershed (from approximately 808,000 in 1950 to nearly 2.4 million in 2000; Fig. 3) and a concurrent decrease in crop production. The decline in crop production was due in large part to declines in agricultural lands, which decreased from 19,414 km^2 to 6,370 km^2 from 1954 to 2002, a reduction of more than two-thirds (Fig. 4). This includes a decrease in the amount of harvested cropland, from 6,528 km^2 in 1954 to 2,494 km^2 in 2002, as well as that of total pastureland (both cropland and non-cropland used for pasture), which decreased from 11,421 km^2 in 1954 to 3,294 km^2 in 2002, with most of the reduction occurring by 1964.

Shifts in animal population were also a factor, albeit a smaller one, in the rise in food and feed imports. The most common types of livestock in the

Altamaha River watershed are chickens, cattle, and hogs. The number of chickens in the watershed has shown a dramatic increase, from approximately 20 million in 1954 to over 260 million in 2002 (Fig. 5a). This increase was almost exclusively due to an increase in broiler chickens raised for meat; the standing stock of older layer chickens has increased by only a few million since 1954 and has actually declined from its high in 1969. Approximately 45% of the increase in chicken population has taken place since 1992, when the rate of chicken increase in the Altamaha watershed tripled. The total number of cattle and calves remained relatively constant throughout the study period (averaging 382,586), but there was an increase in the number of beef cattle and a concurrent decline in the number of dairy cows, which require more nutrients than beef cows (Fig. 5b). The number of hogs varied from 300,000 to 450,000 between 1954 and 1979, after which it declined sharply to less than 60,000 animals in 2002 (Fig. 5c).

Net atmospheric N deposition

Total atmospheric nitrogen deposition rose most dramatically between 1954 and 1982, from 390 to 762 kg N km^{-2} yr^{-1}, after which it increased only slightly (Table 5). N volatilization from fertilizer, which represents an export of N, was fairly low. N volatilization from animal manure, however, rose steadily, from only 77 kg N km^{-2} yr^{-1} in 1954 to 288 kg N km^{-2} yr^{-1} in 2002. The resulting net atmospheric N deposition increased from 251 to 532 kg N km^{-2} yr^{-1} between 1954 and 1974, but had decreased to 401 kg N km^{-2} yr^{-1} by 2002.

Biological N fixation

Total biological nitrogen fixation declined from 734 kg N km^{-2} yr^{-1} in 1954 to 496 kg N km^{-2} yr^{-1} in 2002, with a high of 1,007 kg km^{-2} yr^{-1} in 1982 (Table 5). These patterns were primarily driven by changes in nitrogen fixation by crops, which accounted for 84–91% of the total biological nitrogen fixation in any given year. Although most crops associated with nitrogen-fixing bacteria declined steadily over the study period, particularly pastureland (see Fig. 4), there were dramatic rises and subsequent declines in both soybean and non-alfalfa hay production.

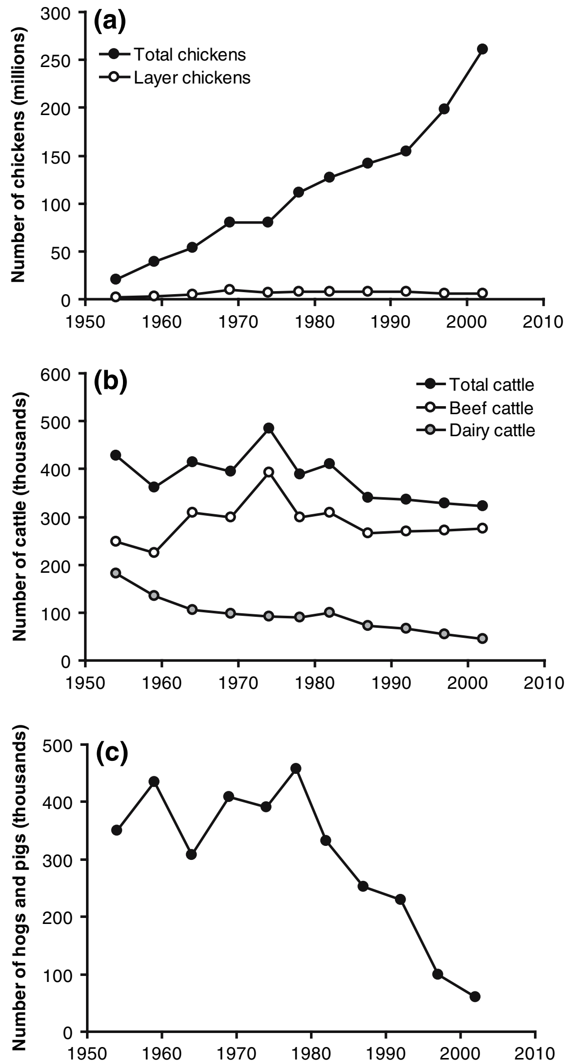


Fig. 5 Number of (**a**) chickens, (**b**) cattle, and (**c**) hogs and pigs in the Altamaha watershed, 1954–2002. *Source*: U.S. Bureau of the Census and USDA Agricultural Censuses, 1954–2002

Total N fixation in forestland decreased overall between 1974 and 2002, from 91 to 59 kg N km^{-2} yr^{-1} (Table 5). This was due primarily to a decrease in oak-hickory forest area and therefore a reduction in black locust N fixation. However, this may be the result of differences in Forest Inventory Analysis classification, as 2003 data are substantially more detailed than 1989 data.

Non-food crop export

N and P production in export crops (cotton and tobacco) was generally quite small, accounting for 2%

or less of total N inputs and 1% or less of total P inputs in most years (Tables 5 and 6). However, unusually high values of crop export (18% of total N and 12% of total P inputs) were observed in 1964 due to extremely high tobacco production in the watershed at that time.

Dominant sources

Fertilizer tended to be the most important input of N to the watershed, and the large changes in fertilizer use over the course of the study period were an important driver of change in the overall N budget (Fig. 6). Fertilizer contributed 26% of total new N inputs in 1954 and rose to 48% of inputs in 1964 before steadily falling back to 27% in 2002. Fertilizer was followed in importance by biological N fixation (BNF), although the contribution of BNF to total input declined over the course of the study period, from 38 to 19%. Net food and feed import accounted for 25% of new N inputs in 1954, fell to 16% by 1974, then rose to 40% in 2002. The increase in net food and feed import was the primary reason for the overall increase in N inputs over the study period. The proportion accounted for by net atmospheric deposition rose slightly over the study period, from 13% to 16% of total N inputs, with a high of 18% in 1992.

The dominant source of phosphorus to the watershed was also fertilizer, which contributed an average of 68% of new P inputs. However, its relative importance declined from 67% in 1954 and 78% in 1964 to only 55% in 2002. Changes in the budget were driven primarily by changes in P fertilizer use. Net food and feed import is now more important as a percentage of total P inputs than in the past, contributing 46% in 2002.

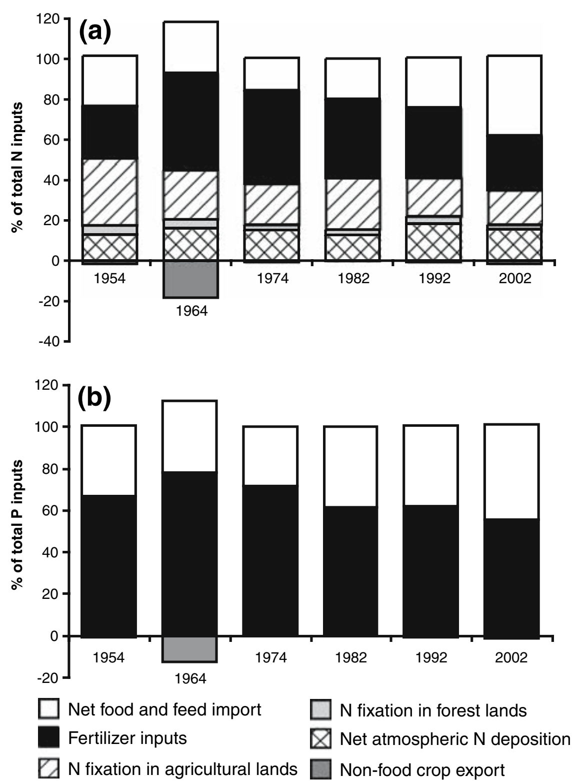


Fig. 6 (**a**) Nitrogen and (**b**) phosphorus inputs to the Altamaha watershed as a percentage of total inputs

Spatial distribution

When nutrient budgets were partitioned across the watershed, most sub-watersheds followed the overall trend of a peak in N inputs in 1982 as compared to 1954 and then either held constant or declined by 2002. P inputs to most sub-watersheds peaked in 1974 and then decreased to levels below those of 1954 (Fig. 7a; Tables 7–10). Below, we examine trends in the spatial patterns of individual inputs.

Fertilizer

Fertilizer inputs followed the same patterns for both N and P, and tended to be highest in the middle portions of the watershed (Fig. 7b). The Lower Ocmulgee consistently had the greatest inputs of fertilizer, followed by the Little Ocmulgee and Ohoopee sub-watersheds (sub-watershed locations are shown in Fig. 1). Residential fertilizer use was not included in these budgets since it was not available for the entire study period. However, residential fertilizer use in the United States as a whole nearly doubled between 1987 and 2001 (Ruddy et al. 2006) and thus, the proportion of nutrient inputs to the Altamaha watershed contributed by non-farm fertilizer use in the earlier parts of the study period can be expected to be negligible. In later years, residential fertilizer use accounted for an additional 12 kg N km^{-2} yr^{-1} and 1 kg P km^{-2} yr^{-1} in 1992 and 11 kg N km^{-2} yr^{-1} and 1 kg P km^{-2} yr^{-1} in 2001, which was less than 2% and less than 0.5% of the total N and P fertilizer use in the watershed, respectively. However, in the Upper Ocmulgee, residential fertilizer use accounted for as much as 10% of total fertilizer N and 3% of total fertilizer P use.

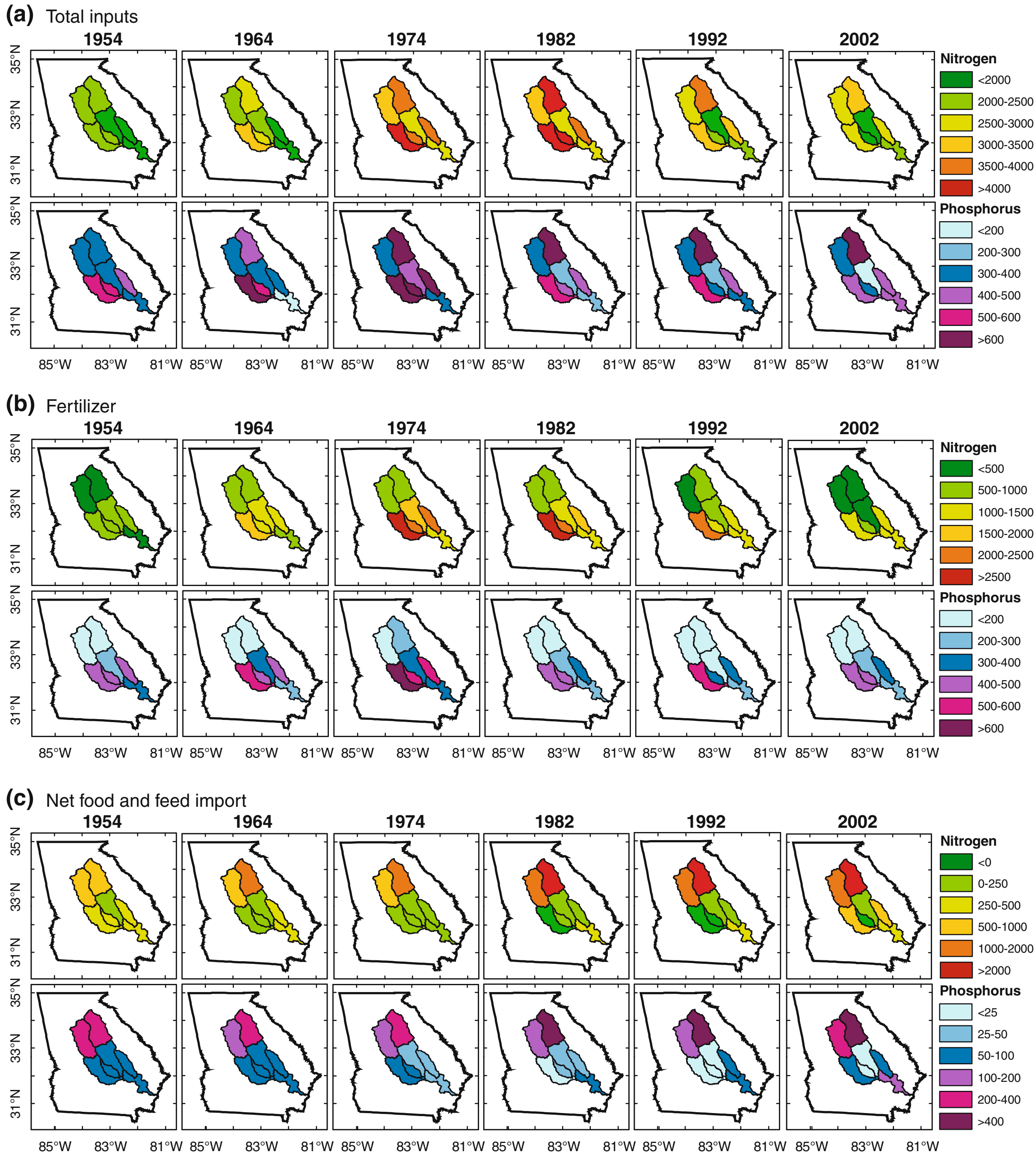


Fig. 7 Spatial distribution of (**a**) total N and P inputs, (**b**) N and P fertilizer inputs, and (**c**) N and P in net food and feed import to sub-watersheds of the Altamaha watershed for target years between 1954 and 2002. All values in kg km^{-2} yr^{-1}. Note that scales differ

Food and feed import

Import of both N and P in net food and feed followed a pattern opposite from that of fertilizer and was lowest in the middle region of the watershed, in the Little and Lower Ocmulgee and Lower Oconee sub-watersheds. These sub-watersheds also led in crop production, with the Little and Lower Ocmulgee

Table 7 Total nitrogen inputs to Altamaha sub-watersheds in 1954, 1964, 1974, 1982, 1992, and 2002

	1954	1964	1974	1982	1992	2002
Upper Oconee	2,146	2,672	3,938	4,289	3,866	3,876
Lower Oconee	1,604	2,115	2,970	2,883	1,962	1,593
Upper Ocmulgee	2,111	2,383	3,064	3,067	2,800	2,565
Lower Ocmulgee	2,171	3,027	4,409	4,338	3,191	2,670
Little Ocmulgee	2,044	2,513	3,770	4,010	2,418	1,875
Ohoopee	1,946	1,284	3,758	3,898	3,092	2,502
Lower Altamaha	1,491	445	2,609	2,718	2,490	2,029

All numbers in kg N km^{-2} yr^{-1}

sub-watersheds actually showing a net export of N in food and feed in 1992. Net food and feed imports were highest in all years in the upper reaches of watershed, in the Upper Oconee and Upper Ocmulgee sub-watersheds (Fig. 7c). However, the main drivers of these patterns were different in each case. The Upper Ocmulgee, site of a substantial portion of the major metropolitan area of Atlanta and its extensive suburbs, saw a dramatic increase in human consumption over time. This sub-watershed had the greatest increase in population of any sub-watershed in both percentage and absolute terms (Fig. 3) and accounts for over 50% of the total population of the greater Altamaha watershed. This growth resulted in increased human nutrient requirements leading to greater import of food. In contrast, the net food and feed import in the Upper Oconee was dominated by increased animal consumption. Nearly all the increase in chicken population in the greater Altamaha watershed was localized within the Upper Oconee sub-watershed (the rate of increase in chickens doubled in this sub-watershed after 1992), and it was also the only sub-watershed with an overall increase in cattle populations. Coupled with steadily declining crop production in both sub-watersheds, the increased demand for food and feed in these two sub-watersheds drove a rise in net import.

Net atmospheric N deposition

Net atmospheric N deposition was lowest in the Upper Oconee, where the high animal populations discussed above resulted in large losses due to manure volatilization. Poultry, and especially broiler chickens, have higher rates of manure volatilization than other types of livestock. In addition, volatilization is higher when animals spend more time indoors (Battye et al. 1994), and chicken production in north Georgia is generally large and industrialized (Centner 2002). This resulted in a negative net atmospheric deposition of nitrogen by 2002, which indicates that this sub-watershed has now become a net source of atmospheric N.

Biological N fixation

N inputs from cropland fixation were highest in the Lower Ocmulgee sub-watershed. N fixation by forestlands also varied among sub-watersheds, due primarily to differences in symbiotic fixation by locust (which was highest in the upper portions of the watershed) and by alder (which was highest in the Lower Oconee and Lower Altamaha sub-watersheds).

Overall nutrient distribution

Total nutrient inputs were fairly evenly distributed among sub-watersheds in 1954, with slightly lower inputs to the Lower Oconee and Lower Altamaha sub-watersheds and slightly higher inputs to the Lower Ocmulgee (Tables 7–10; Fig. 7a). Differences among the sub-watersheds increased over time, primarily due to changes in fertilizer, the dominant input to most sub-watersheds throughout the study period, although changes in net food and feed import also played a role in some places. By 2002, the Upper Oconee sub-watershed had N inputs more than twice as high and P inputs more than three times as high as those of the Lower Oconee.

Discussion

In 2002, estimated nutrient inputs into the watershed of the Altamaha River were 2,582 kg N km^{-2} yr^{-1} and 412 kg P km^{-2} yr^{-1}. These numbers represent an

Table 8 Nitrogen inputs to Altamaha sub-watersheds in 1954, 1964, 1974, 1982, 1992, and 2002

	Atm. N. dep.	Fertilizer	Net food and feed import	Biol. N fix. in agric. lands	Biol. N fix. in forest lands
Upper Oconee					
1954	220	284	791	722	160
1964	204	563	1,137	607	161
1974	395	915	1,683	798	161
1982	153	863	2,400	760	119
1992	279	516	2,328	626	118
2002	−57	379	2,845	642	71
Lower Oconee					
1954	270	510	201	553	99
1964	386	1,009	216	393	111
1974	586	1,640	37	611	111
1982	578	1,287	26	895	100
1992	649	726	34	436	128
2002	635	490	93	327	69
Upper Ocmulgee					
1954	257	259	813	678	126
1964	366	513	808	571	126
1974	587	833	966	568	126
1982	566	726	1,121	533	122
1992	601	461	1,247	368	123
2002	546	344	1,245	372	60
Lower Ocmulgee					
1954	244	881	254	757	69
1964	350	1,744	135	727	71
1974	539	2,834	9	1,017	71
1982	523	2,614	−263	1,423	66
1992	582	2,144	−315	774	93
2002	461	1,270	564	465	49
Little Ocmulgee					
1954	243	757	325	695	56
1964	358	1,498	231	366	60
1974	545	2,434	23	748	60
1982	523	2,165	1	1,277	54
1992	619	1,384	−154	532	73
2002	623	910	−49	405	46
Ohoopee					
1954	263	744	323	626	39
1964	368	1,471	316	401	43
1974	560	2,391	67	755	43
1982	509	1,930	122	1,304	47
1992	579	1,492	224	756	63
2002	451	1,060	544	463	36

Table 8 continued

	Atm. N. dep.	Fertilizer	Net food and feed import	Biol. N fix. in agric. lands	Biol. N fix. in forest lands
Lower Altamaha					
1954	278	463	356	366	51
1964	383	916	314	213	53
1974	561	1,489	130	393	53
1982	499	1,226	259	690	55
1992	559	1,151	294	434	70
2002	369	1,021	344	293	56

All numbers in kg N km^{-2} yr^{-1}

Table 9 Total phosphorus inputs to Altamaha sub-watersheds in 1954, 1964, 1974, 1982, 1992, and 2002

	1954	1964	1974	1982	1992	2002
Upper Oconee	374	456	603	680	608	636
Lower Oconee	349	379	417	273	202	180
Upper Ocmulgee	344	341	391	333	312	321
Lower Ocmulgee	561	607	732	518	526	482
Little Ocmulgee	508	536	626	456	342	308
Ohoopee	492	371	602	408	419	436
Lower Altamaha	331	170	392	290	337	450

All numbers in kg P km^{-2} yr^{-1}

increase of 629 kg N km^{-2} yr^{-1} and 3 kg P km^{-2} yr^{-1} as compared to 1954. N inputs peaked in 1982 and P inputs peaked in 1974. There are no older data with which to compare these estimates, but the results obtained for 2002 were comparable to nitrogen inputs presented by Castro et al. (2003) in their analysis of a series of watersheds on the Atlantic and Gulf coasts of the United States. Their study calculated inputs of 2,830 kg N km^{-2} yr^{-1} to the Altamaha watershed, as compared to 2,582 kg N km^{-2} yr^{-1} in this study. Nutrient inputs calculated by Asbury and Oaksford (1997) were far higher than those presented here, at 5,470 kg N km^{-2} yr^{-1} and 1,380 kg P km^{-2} yr^{-1}. This is most likely a result of differences in methodology, including the use of animal excretion rates that were in some cases more than triple those used in the current study.

The majority of the nutrients entering the Altamaha River watershed over the study period have been agriculturally derived, consisting primarily of inputs due to fertilizer and biological N fixation in agricultural lands. This is consistent with previous reports (Asbury and Oaksford 1997; Castro et al. 2003). However, the relative importance of the different sources of nitrogen has shifted over time. Biological N fixation by crops was the most important source of new N to the Altamaha watershed in the 1950s, but was replaced by increasing inputs of fertilizer N (which peaked in 1974) and then by increases in net food and feed import (driven primarily by concurrent increases in animal consumption and declines in crop production). The overall increase in fertilizer use coincided with a decline in agricultural land—both crop and pastureland—in the watershed (Fig. 4). It is possible that some of the commercially sold fertilizer was applied to golf courses and the like, which would not be included in the estimate of cultivated land, but it is also likely that there has been an increase in the amount of fertilizer used per unit area. This may be due to changes in growing techniques. Crop yields in the watershed have risen substantially since 1954, reflecting a global pattern of dramatic increases in crop yields per unit area due to increased fertilizer application, especially during the 1960s (Tilman et al. 2002). There have also been shifts in the crops that are cultivated: the percentage of harvested cropland producing soybeans increased from 3 to 21% and the percentage producing peanuts increased from 6 to 12% over the course of the study period.

Table 10 Phosphorus inputs to Altamaha sub-watersheds in 1954, 1964, 1974, 1982, 1992, and 2002

	Fertilizer	Net food and feed import
Upper Oconee		
1954	155	223
1964	175	281
1974	216	388
1982	165	516
1992	128	480
2002	125	511
Lower Oconee		
1954	278	74
1964	315	64
1974	388	32
1982	246	27
1992	180	24
2002	161	21
Upper Ocmulgee		
1954	141	206
1964	160	182
1974	197	196
1982	139	195
1992	114	198
2002	113	208
Lower Ocmulgee		
1954	480	85
1964	544	63
1974	670	70
1982	500	22
1992	530	6
2002	418	81
Little Ocmulgee		
1954	413	99
1964	467	69
1974	575	56
1982	414	44
1992	342	4
2002	300	16
Ohoopee		
1954	405	93
1964	459	81
1974	565	44
1982	369	41
1992	369	53
2002	349	94
Lower Altamaha		
1954	252	82
1964	286	68
1974	352	42
1982	234	57
1992	285	54
2002	336	120

All numbers in kg P km^{-2} yr^{-1}

Net food and feed import, which reflects changing populations of livestock and humans as well as crop production, was another important and growing source of nutrients to the watershed. There is less and less cropland producing food and feed for the growing populations of both animals and people in the Altamaha, resulting in the need to import those nutrients from outside the watershed. The large increase in chicken population (from 20 million to over 260 million between 1954 and 2002), taken together with decreased pastureland, also reflects a national trend towards concentrating livestock in animal feeding operations (Centner 2001, 2003).

The finding that nutrient inputs to the Altamaha watershed were lower in 2002 than at mid-points in 1974 and 1982 indicates that increases in watershed nutrient loading to the Altamaha took place in the early portion of the study period, between 1954 and 1982. These results are driven largely by the change in fertilizer input in the watershed, which decreased by half or more between 1977 (the high point) and 2001. This finding is consistent with the long-term pattern of nitrogen input to the Mississippi River watershed, wherein total N inputs leveled off after approximately 1974 (McIsaac et al. 2002). In contrast, N inputs to the Waquoit Bay (Bowen and Valiela 2001) and Neuse River (Stow et al. 2000) watersheds both continued to increase due to rises in wastewater disposal and animal sources, respectively. N loading to the Chesapeake Bay has also continued to increase since the 1950s due to increases in both fertilizer use and import of animal feed (Kemp et al. 2005). There is less information on P, but inputs to the Neuse River watershed remained approximately constant between 1974 and 1992 (Stow et al. 2000). However, Baker and Richards (2002) found a decrease in P inputs to two watersheds in Ohio between 1975 and 1995 due to declines in phosphorus fertilizer inputs.

Numerous studies have found a positive correlation between nutrient input to a watershed and downstream export (e.g. Boyer et al. 2006; Parfitt et al. 2006; Schaefer and Alber 2007). Smith et al. (1997) used the SPARROW model to estimate N and P export for 1987 from the same seven sub-watersheds considered here. When these were compared with nutrient inputs estimated here (the average of our 1982 and 1992 estimates), sub-watershed nutrient input estimates were not significantly correlated with export. However, those sub-watersheds with higher inputs did tend to have higher export: the Upper Oconee, which had the highest inputs of both N and P after 1974, had the highest export of both nutrients. The Lower Ocmulgee, which had the second highest inputs, had the second highest export of N and the third highest export of P. Moreover, these two sub-watersheds also have the highest instream concentrations of both inorganic N and total P (Weston 2005).

The molar ratio of nitrogen to phosphorus in an aquatic system can be used to determine whether it is nitrogen- or phosphorus-limited (Howarth 1988). Temperate estuaries are often N-limited, and are thought to become more so with increasing human inputs to a watershed (Howarth et al. 1996). Higher urban populations have been correlated with increased phosphorus loading to watersheds and resulting lower N:P ratios (Caraco 1995). In this study, the atomic N:P ratio of inputs to the Altamaha watershed was generally lower than the Redfield Ratio of 16:1, suggesting N limitation. However, P inputs remained relatively constant while N inputs varied. As a consequence, the N:P ratio of inputs increased from 10.5 to 13.8 (with a peak of 18.3 in 1982). The lower Oconee and Upper Ocmulgee tended to have higher N:P ratios in inputs than other sub-watersheds, and were the only two with ratios over 16 in 2002. The N:P ratios of instream nutrient concentrations in these sub-watersheds were calculated based on an analysis of USGS water quality stations performed by Weston (2005). Instream N:P ratios between the 1970s and the early 2000s were always less than those calculated based on inputs, ranging from 7.3 to 15.7. N and P may be transported differently within the watershed due to differences in their biogeochemical pathways, particularly due to N loss via denitrification, so the change in N:P ratio is not surprising. Nevertheless, the observed increase in inputs should result in increased delivery, and if the inputs in N are increasing faster than those in P, these differences should eventually be reflected in instream ratios. Such a trend towards increasing N enrichment was observed in the Neuse River, where a decline in P inputs and a rise in N inputs to the estuary resulted in an increasing N:P ratio between 1970 and 2003 (Paerl et al. 2004).

These data can be used to guide management efforts aimed at reducing nutrient inputs to the watershed. The fact that current levels of phosphorus input are not substantially above those of the 1950s suggests that nitrogen inputs are a more pressing concern in most sub-watersheds. Since inputs were primarily due to agricultural rather than urban sources, attention to agricultural best management practices would most likely help reduce inputs to the watershed. Efforts to reduce nutrient inputs should focus on fertilizer in the middle portion of the watershed, and on animal agriculture in the Upper Oconee sub-watershed, where the majority of livestock production takes place. Increasing human populations in the Upper Ocmulgee sub-watershed may also be a concern in the future with the continued expansion of Atlanta and its suburbs, and therefore attention in this sub-watershed should be focused on controlling nutrients from wastewater treatment plants and septic tanks.

Whether or not further increases in nutrient inputs take place in the watershed of the Altamaha River will depend on future trends in agriculture and human populations. Fertilizer inputs to the watershed declined between 1977 and 2002, and if fertilizer application becomes more efficient in the future, inputs could continue to decrease. However, these decreases could be offset if inputs of non-commercial fertilizers increase with increasing urban and suburban populations. In addition, the production of food and feed to sustain increases in both human and animal populations may also have to intensify. Thus, further increases in nutrient inputs to the watershed can be expected.

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